U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-156136

Empirical Studies of the Relationships Between Emissions and Visibility in the Southwest

Technology Service Corp, Santa Fe, NM

Prepared for

Environmental Protection Agency, Research Triangle Park, NC

Sep 79

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/5-79-009
September 1979

Air

PB80-156136

EPA

Empirical Studies of the Relationship Between Emissions and Visibility in the Southwest

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-450/5-79-009		PB 80 156136

4. TITLE AND SUBTITLE	5. REPORT DATE
Empirical Studies of the Relationship Between Emissions and Visibility in the Southwest	September 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	**8. PERFORMING ORGANIZATION REPORT NO.**
Marilyn Marians and John Trijonis	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	**10. PROGRAM ELEMENT NO.**
Technology Service Corporation Route 7, Box 124-K Santa Fe, New Mexico 87501	**11. CONTRACT/GRANT NO.** Grant 802015
12. SPONSORING AGENCY NAME AND ADDRESS	**13. TYPE OF REPORT AND PERIOD COVERED**
U.S. Environmental Protection Agency Research Triangle Park, N.C. 27711	Interim May 1978-March 1979 **14. SPONSORING AGENCY CODE**

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Historical emission trends of SO_x, NO_x, and NMHC are determined year-by-year from 1948 to 1975 for four Southwestern states (Arizona, Colorado, Nevada, and Utah). Trends in visibility levels (medians and other percentiles) are documented for the period 1948-1976 at 12 airports in the Southwest.
Two analyses are used to relate emission changes to variations in regional extinction levels. The first analysis examines the air quality changes associated with a 90% reduction of Southwestern SO_x emissions during a nine-month copper strike and estimates the extinction produced by SO_x emissions on various spatial scales. The second analysis involves regression studies relating historical extinction levels from 1948-1975. Because of limitations in the analytical methods, there is a high degree of uncertainty in many of the results. However, the studies do provide insights into the effects of aerosol precursor emissions on extinction at various distances from sources. In the case of mesoscale effects of SO_x in the Southwest, quantitative coefficients are proposed which link emissions to regional extinction.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution Aerosols Sulfates Visibility Sulfur oxides emissions	Southwest	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (9-73)

EPA-450/5-79-009

Empirical Studies of the Relationship Between Emissions and Visibility in the Southwest

by

Marilyn Marians and John Trijonis

Technology Service Corporation
Route 7, Box 124-K,
Santa Fe, New Mexico 87501

Grant No. 802815

EPA Project Officers: John Bachmann (OAQPS),
William E. Wilson, and Thomas G. Ellestad (ESRL)

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

September 1979

This report has been reviewed by the Strategies and Air Standards Division of the Office of Air Quality Planning and Standards, EPA, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of EPA. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use. Copies of this report are available through the Library Services Office (MD-35), U. S. Environmental Protection Agency, Research Triangle Park, N. C. 27711, or from National Technical Information Services, 5285 Port Royal Road, Springfield, Virginia 22161.

Publication No. EPA-450/5-79-009

ABSTRACT

Historical emission trends of SO_x, NO_x, and NMHC are determined year-by-year from 1948 to 1975 for four Southwestern states (Arizona, Colorado, Nevada, and Utah). Trends in visibility levels (medians and other percentiles) are documented for the period 1948-1976 at 12 airports in the Southwest.

Two analyses are used to relate emission changes to variations in regional extinction levels. The first analysis examines the air quality changes associated with a 90% reduction of Southwestern SO_x emissions during a nine-month copper strike and estimates the extinction produced by SO_x emissions on various spatial scales. The second analysis involves regression studies relating historical changes in emissions to historical extinction levels from 1948-1975. Because of limitations in the analytical methods, there is a high degree of uncertainty in many of the results. However, the studies do provide insights into the effects of aerosol precursor emissions on extinction at various distances from sources. In the case of mesoscale effects of SO_x in the Southwest, quantitative coefficients are proposed which link emissions to regional extinction.

This report was submitted to the U.S. Environmental Protection Agency by Technology Service Corporation in partial fulfillment of Grant 802815. Work on this project started in May 1978 and was completed in March 1979.

CONTENTS

ABSTRACT iii

FIGURES. vii

TABLES ix

1. INTRODUCTION AND SUMMARY 1
   - Summary of Conclusions. 3
   - Future Work 5

2. HISTORICAL EMISSION TRENDS IN THE SOUTHWEST. 7
   - General Magnitude of Emissions. 7
   - Historical Changes in Emissions 8
   - Primary Sulfate Emissions 21
   - Emission Trends for Individual Air Basins 22

3. HISTORICAL VISIBILITY TRENDS IN THE SOUTHWEST. 23
   - Changes in Observation Locations. 23
   - Historical Visibility Trends. 24

4. REGIONAL EXTINCTION/EMISSION COEFFICIENTS BASED ON THE 1967-1968 COPPER STRIKE. 42
   - Methodology 42
   - Extinction/Emission Coefficients for SO_x. 48

5. REGIONAL EXTINCTION/EMISSION COEFFICIENTS BASED ON HISTORICAL EMISSION CHANGES FROM 1948 TO 1975. 55
   - Methodology 55
   - Regression Analysis for Arizona Sites 57
   - Regression Analyses for Other Locations 65

6. CONCLUSIONS AND ILLUSTRATIVE APPLICATIONS. 70
   - Extinction/Emission Coefficients for the Southwest. 70
   - Illustrative Applications 72

REFERENCES 74

APPENDIX A 75
APPENDIX B 94
APPENDIX C 100
APPENDIX D 106

FIGURES

Number		Page
1.	Sulfur oxide emission trends in Arizona, 1948-1975.	9
2.	Sulfur oxide emission trends in Colorado, 1948-1975	10
3.	Sulfur oxide emission trends in Nevada, 1948-1975	11
4.	Sulfur oxide emission trends in Utah, 1948-1975	12
5.	Nitrogen oxide emission trends in Arizona, 1948-1975.	13
6.	Nitrogen oxide emission trends in Colorado, 1948-1975	14
7.	Nitrogen oxide emission trends in Nevada, 1948-1975	15
8.	Nitrogen oxide emission trends in Utah, 1948-1975	16
9.	Nonmethane hydrocarbon emission trends in Arizona, 1948-1975	17
10.	Nonmethane hydrocarbon emission trends in Colorado, 1948-1975	18
11.	Nonmethane hydrocarbon emission trends in Nevada, 1948-1975	19
12.	Nonmethane hydrocarbon emission trends in Utah, 1948-1975	20
13.	Long-term visibility trends at Phoenix.	26
14.	Long-term visibility trends at Tucson	27
15.	Long-term visibility trends at Denver	28
16	Long-term visibility trends at Salt Lake City	29
17.	Long-term visibility trends at Fort Huachuca.	30
18.	Long-term visibility trends at Prescott	31
19.	Long-term visibility trends at Winslow.	32
20.	Long-term visibility trends at Colorado Springs	33

Number		Page
21.	Long-term visibility trends at Grand Junction	34
22.	Long-term visibility trends at Pueblo	35
23.	Long-term visibility trends at Ely.	36
24.	Long-term visibility trends at Cheyenne	37
25.	Airport weather stations and NASN monitoring sites used to determine air qulaity changes during the 1967-1968 copper strike	43
26.	Seasonally adjusted changes in extinction during the copper strike, units of $(10^4$ meters$)^{-1}$, compared to the geographical distribution of smelter SO_x emissions.	45
27.	Seasonally adjusted changes in sulfate during the copper strike, units of $\mu g/m^3$, compared to the geographical distribution of smelter SO_x emissions	46
28.	Extinction/emission coefficients based on airport data during the 1968-1968 copper strike.	49
29.	Sulfate/emission coefficients based on NASN data during the 1967-1968 copper strike.	50
30.	Extinction/emission coefficients from airport and NASN data during the 1967-1968 copper strike	51
31.	Log-log plot of extinction/emission coefficient versus distance to smelters.	53
32.	Tucson time series data on extinction and hours of restricted visibility versus historical smelter SO_x emissions for Arizona	60
33.	Phoenix time series data on extinction and hours of restricted visibility versus historical smelter SO_x emissions for Arizona	61
34.	Yearly median extinction at Tucson versus smelter SO_x emissions for Arizona	62
35.	Yearly median extinction at Phoenix versus smelter SO_x emissions for Arizona	63

TABLES

Number		Page
1.	Magnitude of Precursor Emissions in the Southwest, Tons/Day, 1970-1972.	8
2.	Analysis of the Statistical Significance of Observation Site Relocations on Reported Airport Visibilities.	25
3A.	Net Percent Changes in Visibility, 1953-1955 to 1970-1972, Original Analysis (Trijonis and Yuan, 1978a)	39
3B.	Net Percent Changes in Visibility, 1953-1955 to 1970-1972, All Site Relocations Discounted.	40
3C.	Net Percent Changes in Visibility 1953-1955 to 1970-1972, All Significant Site Relocations Discounted.	41
4.	Pairing of Airports and NASN Sites with Smelters Most Likely to Affect Those Sites.	47
5.	Intercorrelation Among Statewide Total Emission Trends, 1948-1975.	56
6.	Historical Extinction-Emission Correlations for Arizona Trend Sites.	58
7.	Regressions of Historical Extinction Levels Versus Historical Smelter SO_x Emission Levels	59

CHAPTER 1

INTRODUCTION AND SUMMARY

Several previous studies have developed models of visibility degradation based on empirical analysis of ambient data (Trijonis and Yuan, 1978a, b; White and Roberts, 1977; Cass, 1976). These empirical models involve multiple regression equations relating extinction levels to corresponding air quality levels. The key parameters determined by the regressions are extinction coefficients per unit mass for individual aerosol species (sulfates, nitrates, organics, and remainder of TSP); these coefficients allow the computation of extinction budgets allocating visibility loss among the various aerosol components. The results of the empirical studies have proven to be consistent with one another and with theoretical predictions based on the Mie theory of aerosol optics (Trijonis and Yuan, 1978a, b; Latimer et al, 1978; Ursenbach et al, 1978; White and Roberts, 1977; Waggoner et al, 1976).

The catch with the existing empirical models is that, even if we know with confidence the extinction coefficients per unit mass for each aerosol species, we need an additional model to predict aerosol concentrations from emissions. That is -- we still must address the problem of determining secondary aerosol concentrations from gaseous precursor emissions and primary aerosol concentrations from particulate emissions. This latter problem is itself quite complex and difficult, especially in the case of secondary aerosols (e.g. sulfates and nitrates), especially for the phenomenon of regional haze (as opposed to an isolated plume), and especially in situations of complex terrain (as is often found in the Southwest United States).

This report uses a new type of empirical model to address the problem of regional haze caused by secondary aerosols in the Southwest. The novelty of the approach is that we attempt to relate extinction not to ambient aerosol data, but directly to emissions of aerosol precursors. The key outputs of the analysis are extinction coefficients per unit emissions of aerosol precursors, with units of $(10^4 \text{ meters})^{-1}/(1000 \text{ tons per day})$.*

*Hereafter abbreviated as $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$.

We attempt to derive these coefficients for SO_x, NO_x, and NMHC emissions on various spatial scales, ranging from the air basin scale ($\lesssim$ 50 miles from the source) to the mesoscale ($\sim$ 50-200 miles from the source) to the synoptic scale ($\sim$ 200-500 miles from the source). Once they are determined, these extinction/emission coefficients can serve as the basis for first approximation calculations concerning the impact of emissions on regional haze in the Southwest.

Two analyses are conducted in attempting to derive extinction/emission coefficients for regional haze in the Southwest. The first analysis is based on visibility and sulfate changes during the 1967-1968 copper strike, when SO_x emissions in the Southwest were reduced over 90% for a nine month period. The second analysis is based on regressions relating historical trends in SO_x, NO_x, and NMHC emissions to corresponding trends in airport visibility data. Because of limitations in these analyses (especially in the regression studies), a high degree of uncertainty exists in our results. In fact, the only extinction/emission coefficient in which we have a fair degree of confidence is the mesoscale coefficient for sulfur oxides. Several of our results, however, should serve as useful checkpoints for future models of regional haze in the Southwest.

This report is organized in six chapters. The remainder of this chapter summarizes our conclusions and recommends future research areas. Chapter 2 presents detailed, year-by-year emission trends from 1948 to 1975 for SO_x, NO_x, and NMHC in the four study states (Arizona, Colorado, Nevada, and Utah) for which we have data on ambient visibility trends. Chapter 2 is supported by three appendices: Appendix A -- explaining the bases for the emission trend calculations; Appendix B -- discussing the issue of primary sulfate emissions from copper smelters and power plants; and Appendix C -- explaining how air basin emission trends can be computed from statewide emission trends. Chapter 3 updates our previous visibility trend study for the Southwest (Trijonis and Yuan, 1978a) and presents visibility trends from 1948 to 1976 at twelve locations. Chapter 4 uses data during the 1967-1968 copper strike to estimate regional extinction/emission coefficients for SO_x. Chapter 5 performs regression studies relating historical visibility trends

at various locations to historical emission trends. Chapter 6 discusses our conclusions and illustrates how extinction/emission coefficients might be applied to estimate the impact of emission sources on regional haze.

SUMMARY OF CONCLUSIONS

Historical Emission Trends in the Southwest (Chapter 2)

- Copper smelters have historically been the overwhelming source of SO_x emissions and, on a tonnage basis, the major source of aerosol precursor emissions in the Southwest. Total smelter SO_x emissions in the Southwest approximately doubled from 1948 to 1973 as increased copper production outdistanced the effects of the air pollution controls that were installed on a few smelters. The recent proliferation of air pollution controls among the Arizona smelters (the dominant group of smelters in the Southwest) helped to reduce Arizona smelter SO_x by 38% from 1973 to 1975 and by 66% from 1973 to 1977. Power plants have recently been a rapidly growing source category for SO_x and now rank second to copper smelters in terms of total Southwest SO_x emissions.

- NO_x emissions have climbed steadily in the Southwest, with an especially rapid rise in the late 1960's and early 1970's. Total NO_x emissions increased by a factor of 5 from 1948 to 1975. The two major source categories for NO_x, power plants and gasoline vehicles, account for nearly all of this rising trend.

- Total NMHC emissions in the Southwest increased by a factor of 3 from 1948 to 1972 and then started a gradual decline. This basically reflects the trend in the dominant source category for NMHC, gasoline vehicles.

Historical Visibility Trends in the Southwest (Chapter 3)

- Visibility exhibited a decreasing trend in the Southwest from the middle 1950's to the early 1970's. Nearly all of the 12 trend study sites showed a net decline in visibility on the order of 10 to 30% from 1953-1955 to 1970-1972. This decrease in visibility is equivalent to an increase in extra extinction (above-and-beyond blue-sky scatter) on the order of 10 to 70% (Trijonis and Yuan, 1978a).

- Since the early 1970's, the declining trend in visibility has apparently reversed. Several trend sites show an increase in median visibility on the order of 5 to 15% from 1970-1972 to 1974-1976.

Regional Extinction/Emission Coefficients Based on the 1967-1968 Copper Strike (Chapter 4)

- The nine-month copper strike of 1967-1968 was accompanied by large decreases in sulfates and increases in visibility in many parts of the Southwest. Statistically significant drops in sulfate occurred out to distances greater than 300 miles from the smelters, and statistically significant increases in visibility occurred out to distances greater than 150 miles from the smelters. Variations in weather were apparently not a factor contributing to these air quality improvements (Trijonis and Yuan, 1978a).

- Both the airport visibility data and NASN sulfate data during the copper strike imply that the mesoscale extinction/emission coefficient for SO_x is .01 to .03 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$. In other words, on a scale of 50 to 200 miles from the source, each 1000 TPD SO_x was apparently associated with an extinction of .01 to .03 $(10^4 \text{ m})^{-1}$. The extinction/emission coefficients based on the airport data may be slightly overestimated (on the order of 10-30%) because of the neglect of concurrent changes in primary particles during the copper strike.

- The copper strike analysis also provided some evidence in support of the following conclusions: (1) regional extinction produced by an SO_x emission source in the Southwest may tend to be inversely proportional to distance from the source; (2) at distances 250-375 miles from the source (within the synoptic scale), the extinction/emission coefficient may be approximately .01 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$; and (3) at distances within 10 to 15 miles from the source (within the air basin scale), the extinction/emission coefficient may be as high as .1 to .25 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$. As indicated by the qualified wording, however, we regard these latter three conclusions as very tenuous.

Regional Extinction/Emission Coefficients Based on Historical Emission Changes from 1948 to 1975 (Chapter 5)

- There are several important limitations to the regression analysis relating yearly extinction levels (based on airport data) to yearly emission levels from 1948 to 1975. One of the most important drawbacks is the intercorrelation that exists among the "independent" emission variables. The historical emission variables (SO_x, NO_x, and NMHC trends for various states) typically correlate with one another at levels of R = .50 to .85 (correlation coefficients). This intercorrelation and the limited number of data points (28 years) make it extremely difficult to isolate the individual effects of all three emission

variables (SO_x, NO_x, and NMHC). Another important drawback is the lack of data on primary particulate emission trends.

- The regression analysis for Arizona is conducted using six data bases (four airports, but two time periods for two of the airports). In all six cases, historical extinction levels correlate best with Arizona smelter SO_x emissions, the R values ranging from .68 to .91. Multiple regressions select Arizona smelter SO_x as (by far) the most significant variable in all six cases and as the only significant variable in five of the cases. These results make sense physically, considering that copper smelters have historically been the overwhelming source of secondary aerosol precursor emissions in Arizona.

- All six Arizona regression analyses yield about the same value for the mesoscale extinction/emission coefficient for SO_x: .04 $\pm$ .005 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$. This value is slightly higher than the .01 - .03 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$ values determined in the copper strike analysis. We tend to place greater faith in the .01 - .03 values because the regression coefficients in the trend analysis may be slightly inflated by the effect of concurrent changes in NO_x, NMHC, and primary particulate emissions.

- Because of problems with respect to intercorrelated emission variables, we could not isolate the effect of NO_x and NMHC on extinction trends in Arizona. However, there are several indications that, although these effects appear to be secondary to the impact of the large SO_x emissions in Arizona, they nevertheless are significant.

- The regression studies for the other four sites (Salt Lake City, Denver, Grand Junction, and Ely) did not fare as well as the Arizona regressions. The analyses did provide some indications that growth in the photochemical precursors (NO_x and NMHC) was the key factor related to visibility changes in the urban areas of Salt Lake City and Denver, and that a measurable impact from the Arizona smelters may extend well north of Arizona. However, because of the lack of consistent regression (extinction/emission) coefficients from site to site, and because of rather low correlations (except for Salt Lake City), we cannot place great faith in the conclusions reached for the non-Arizona sites.

FUTURE WORK

There are several research areas where the work conducted in this project might be fruitfully extended. The most important area for future work is to compare the regional extinction-emission relationships we have found

to the results of other approaches, such as the Systems Applications Incorproated regional grid model for visibility (Latimer et al, 1978), the Teknekron psuedo-spectral regional transport model (Niemann, 1978), simple box model calculations, and other empirical data (e.g. extinction and air quality data at large distances in plumes from isolated sources). In fact, because of uncertainties in our analyses, it may be best to regard our results as a checkpoint for future studies rather than as a useable tool for regional visibility assessment.

The historical trend analysis would be made more complete by adding data on primary particulate emissions. This additional analysis should include fugitive dust sources as well as conventional sources, should consider the size distribution of emitted particles, and should give special attention to the apparently significant contributions of fine silicon particles to Southwestern visibility (Macias el al, 1979). Because of uncertainties and gaps in data on fugitive dust emissions, particle size distributions, and fine silicon emissions, an adequate analysis of primary particulate emission trends would be very difficult to conduct given the present state of knowledge.

Both the copper strike analysis and the trend analysis in this report might be improved by stratifying the data by meteorological class. The important meteorological parameters include precipitation, relative humidity, wind speed, and especially, wind direction. Although a meteorological stratification might strengthen the observed relationships between extinction and emissions, it should be noted that the results based on such a stratification would no longer represent the average regional impacts under all meteorological conditions, but rather the impacts associated with special (e.g. worst-case) meteorology.

The analysis of the copper strike would be improved by obtaining additional data on visibility changes during that period. Our study has been restricted only to data available in computerized form; there are other airports for which hard copy data ave available. Additional data for northern Arizona, southern Utah, northwest New Mexico, and southwest Colorado should help to resolve the apparent discrepancy between the spatial scales of the sulfate changes and visibility changes during the copper strike.

CHAPTER 2

HISTORICAL EMISSION TRENDS IN THE SOUTHWEST

This chapter describes historical emission trends for secondary aerosol precursors in the Southwest. Emissions are presented year-by-year from 1948 to 1975 for sulfur oxides, nitrogen oxides, and normethane hydrocarbons. The trends are provided separately for four states -- Arizona, Colorado, Nevada, and Utah -- in which we also have data on ambient visibility trends.

Appendix A documents the derivation of the emission trend estimates. Many sources of data -- reports of various federal agencies, state agencies, industrial firms, and trade associations -- were considered in compiling the emission trends. As explained in Appendix A, the emission trends were determined only for major source categories: copper smelters, power plants, gasoline vehicles, diesel vehicles, railroads, petroleum industries, industrial boilers, commercial/residential sources, gasoline evaporation, and solvent evaporation. These major source categories account for 80-100% of the SO_x, 90-100% of the NO_x, and 70-90% of the NMHC emissions in the four states studied. Appendix A includes detailed tables listing year-by-year emissions for each source category in each state.

GENERAL MAGNITUDE OF EMISSIONS

Before discussing the historical changes in emissions, it is useful to examine the general magnitude of emissions in order to gain an overall perspective. Table 1 lists average emissions by pollutant and state during 1970-1972, years in which emissions tended to be at or near their historical peak in the Southwest states. It is apparent that, because of a large copper industry, the Southwest tends to be relatively rich in SO_x emissions; in 1970-1972 the four states accounted for only 2½% of nationwide NMHC and NO_x but for 8% of nationwide SO_x. In particular, the copper smelters in Arizona -- which emitted approximately 10 times as much SO_x as the Los Angeles Basin in 1970-1972 (AQMP, 1976) -- have historically been, on a mass basis, the predominant single source of precursor emissions in the Southwest.

TABLE 1. MAGNITUDE OF PRECURSOR EMISSIONS IN THE SOUTHWEST, TONS/DAY, 1970-1972

	SO_x total/(copper smelters)	NO_x total	NMHC total
Arizona	5,840/(5,600)	570	570
Colorado	200	480	760
Nevada	830/(760)	200	210
Utah	650/(430)	290	330
Four State Total	7,520/(6,790)	1,540	1,870
United States Total (EPA, 1976)	92,000	58,000	82,000

HSITORICAL CHANGES IN EMISSIONS

Figures 1 through 12 summarize the historical changes of SO_x, NO_x, and NMHC emissions in the four states under study. The top line in each figure depicts the year-by-year changes in total emissions for each pollutant and each state. The distances between the lines measure contributions from individual source categories.

As indicated in Figures 1 to 4, copper smelters have historically been the dominant source of SO_x emissions in the Southwest. The major factors governing historical changes in smelter emissions have been production levels (including the effects of labor strikes) and air pollution controls. Over the entire study period, copper production more than doubled in Arizona and Nevada but remained approximately constant in Utah. Downward kinks in emissions are evident during years of major labor strikes: 1948-1949, 1954-1955, 1959, and especially the 9 month strike of 1967-1968. Air pollution controls reduced Utah smelter SO_x emissions in the 1950's. Some control of the Arizona smelters started in 1966, but most of the Arizona controls were phased in after 1973. Because of emission controls and because of slightly reduced copper production, Arizona smelter emissions dropped from 5800 TPD in 1973 to 3600 TPD in 1975 (and continued falling to 2000 TPD in 1977).

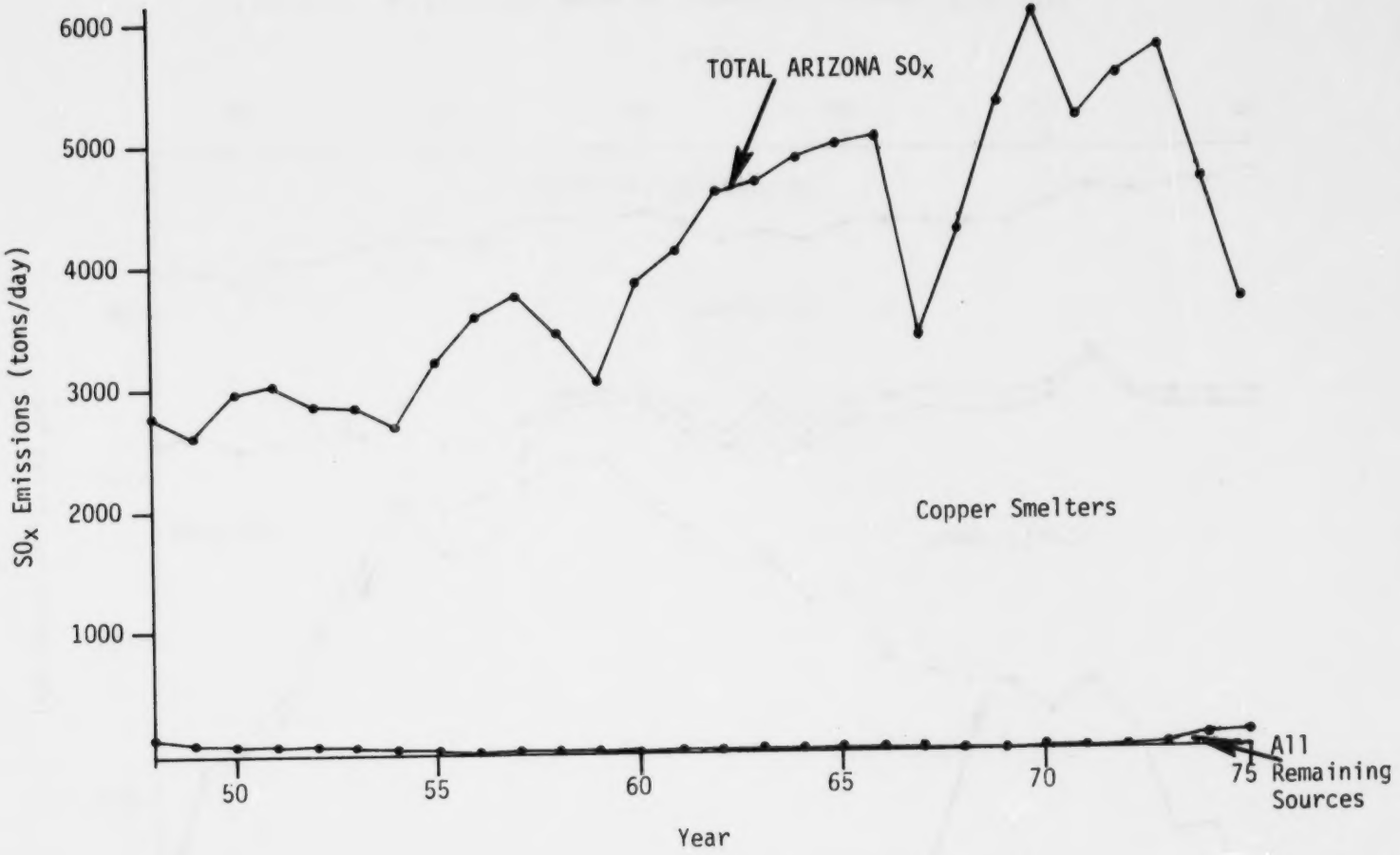


Figure 1. Sulfur oxide emission trends in Arizona, 1948-1975.

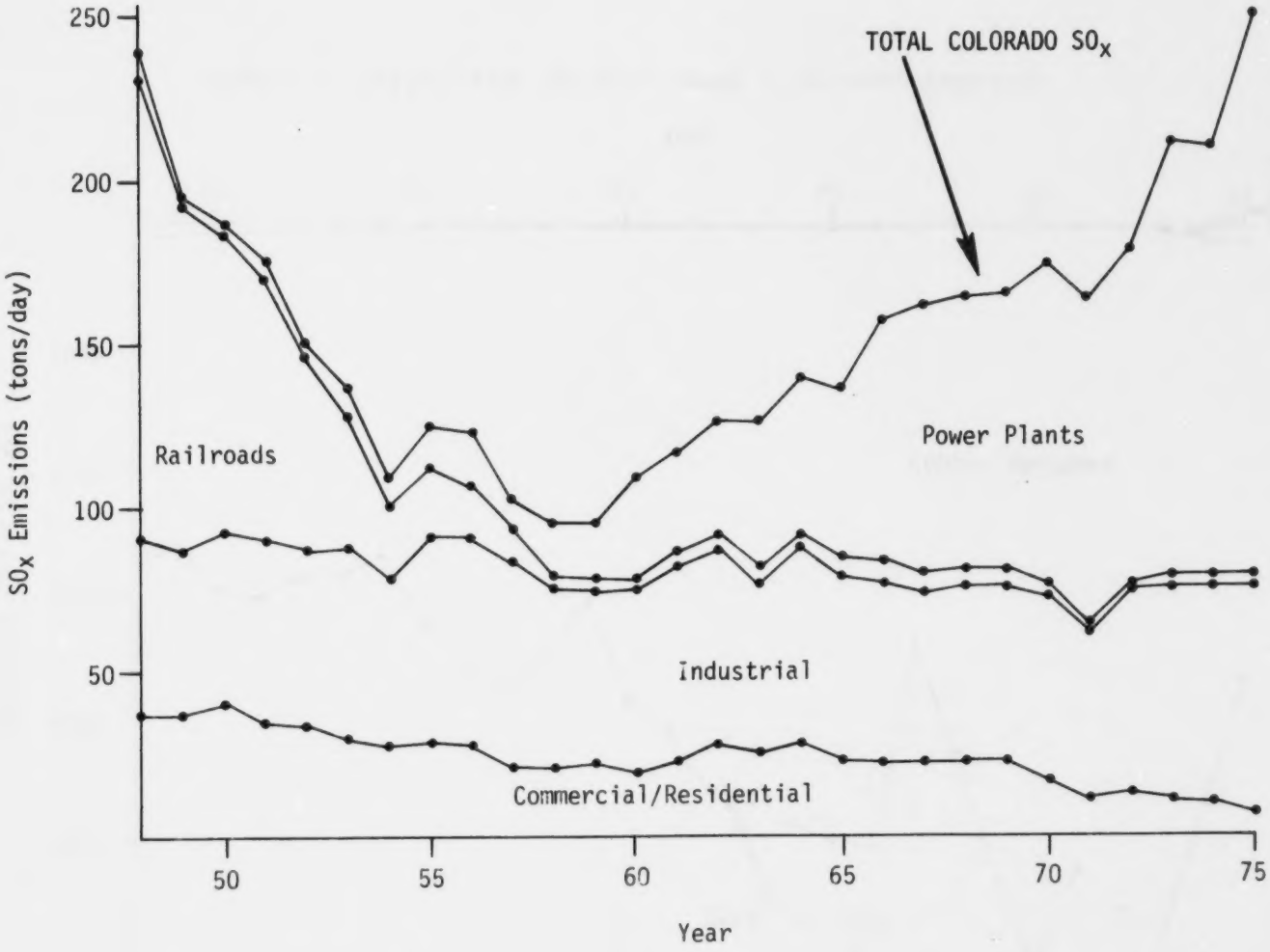


Figure 2. Sulfur oxide emission trends in Colorado, 1948-1975.

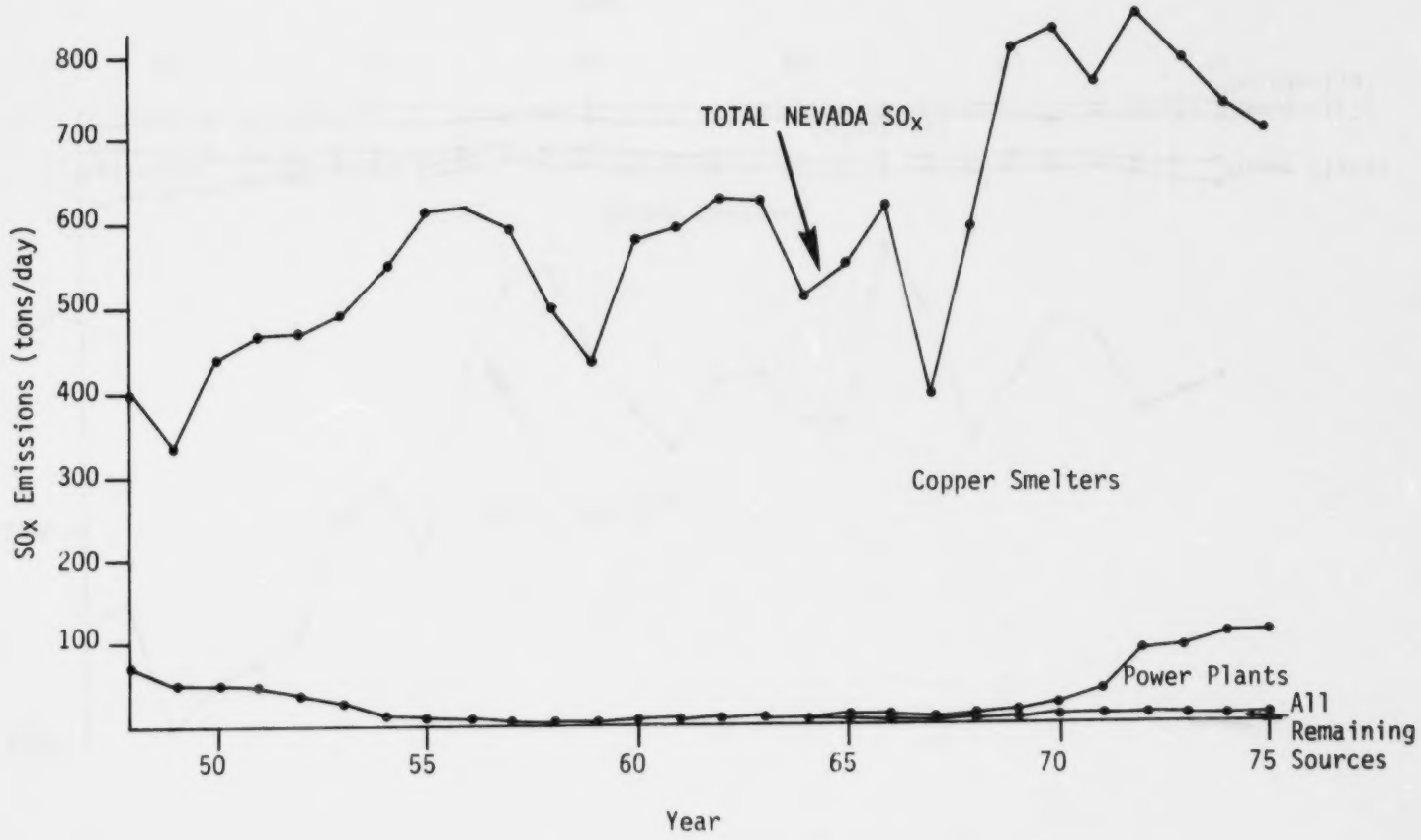


Figure 3. Sulfur oxide emission trends in Nevada, 1948-1975.

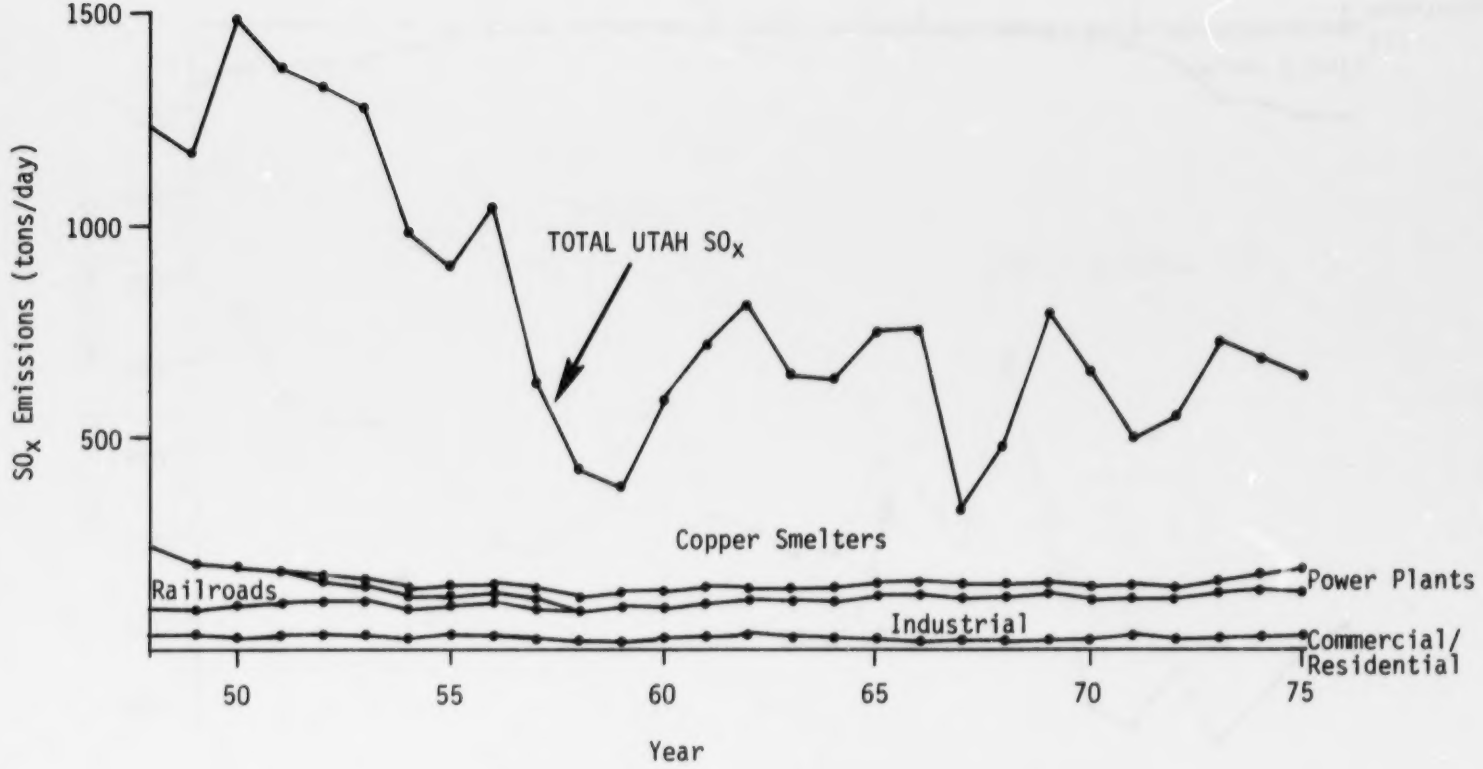


Figure 4. Sulfur oxide emission trends in Utah, 1948-1975.

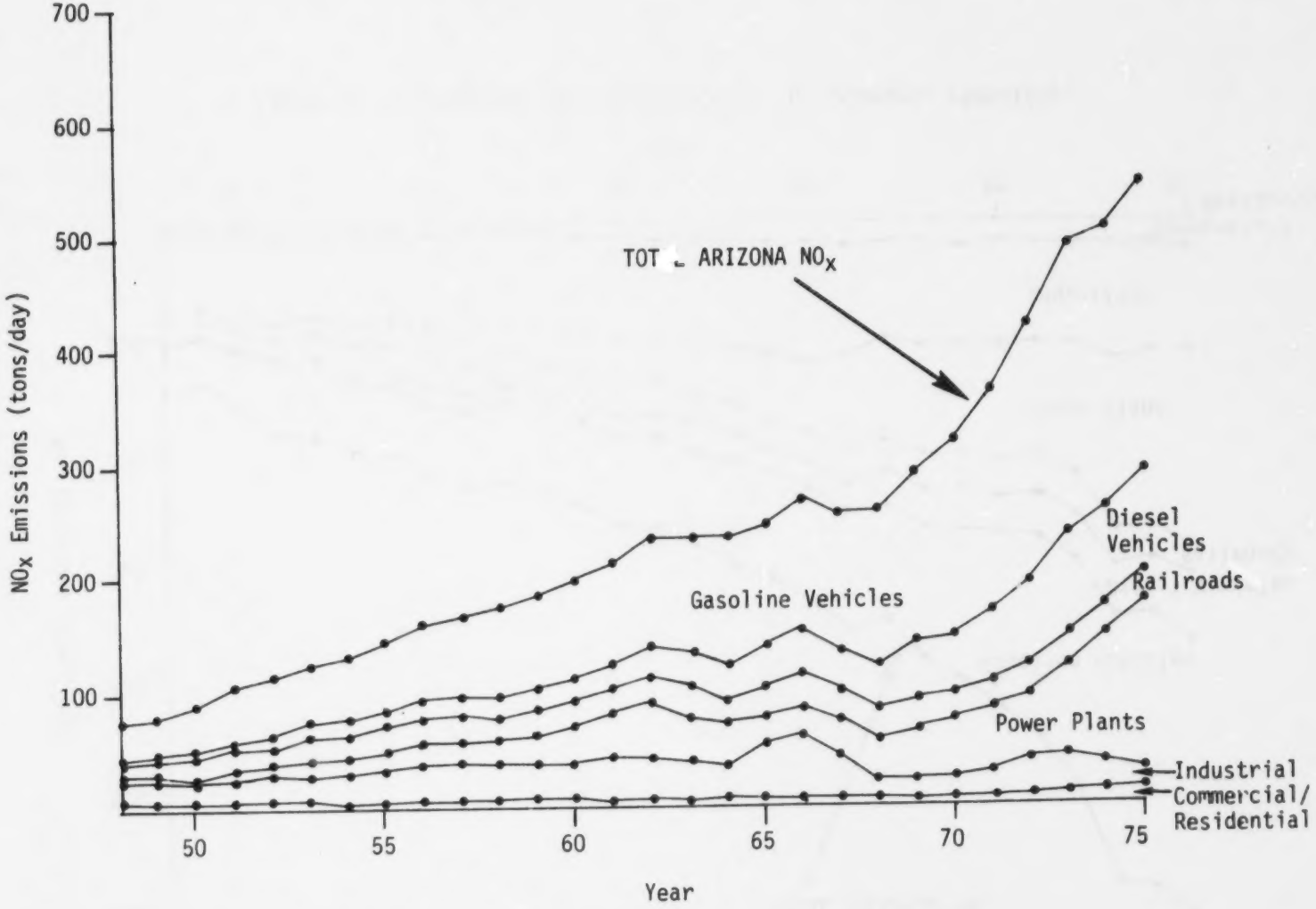


Figure 5. Nitrogen oxide emission trends in Arizona, 1948-1975.

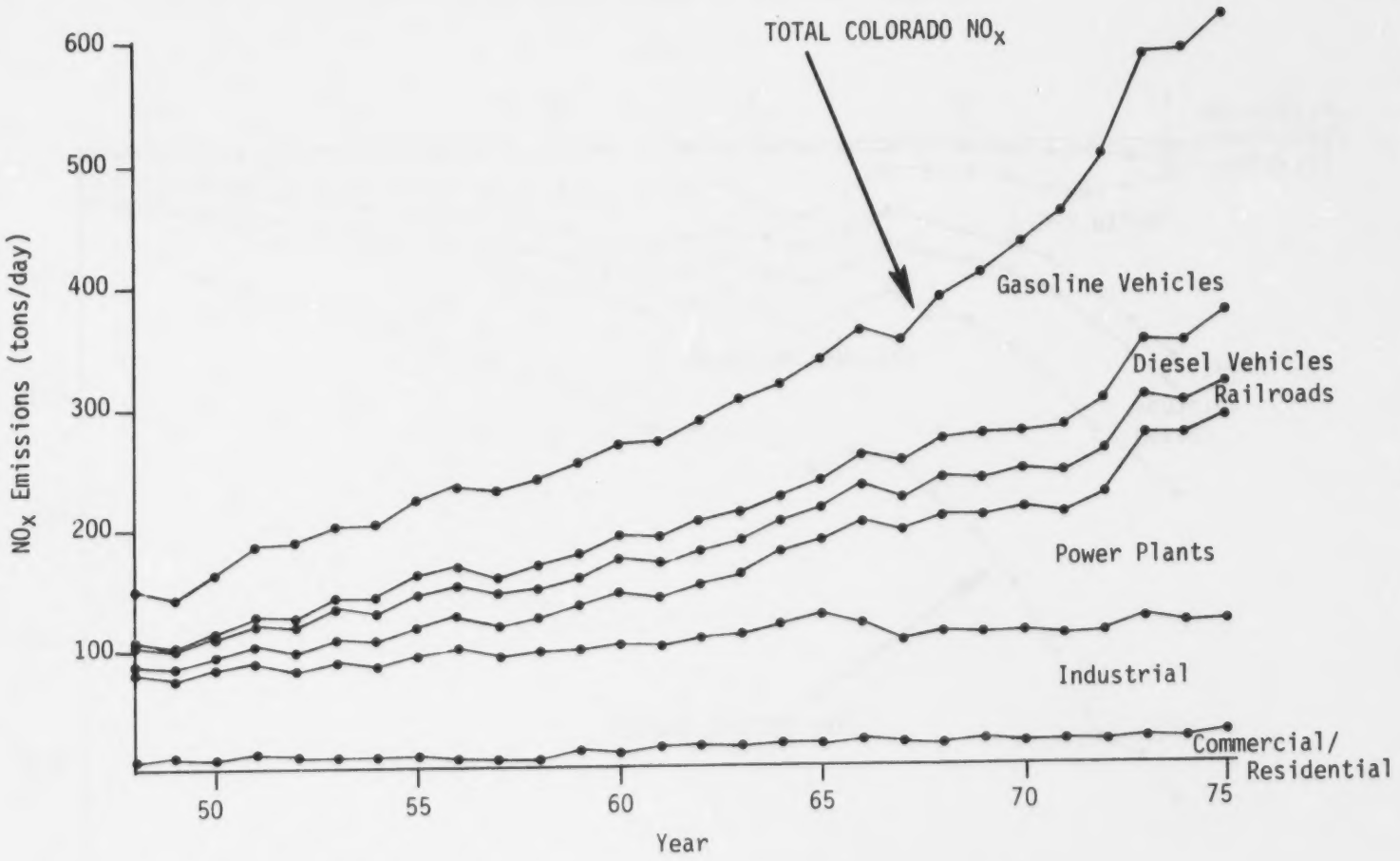


Figure 6. Nitrogen oxide emission trends in Colorado, 1948-1975.

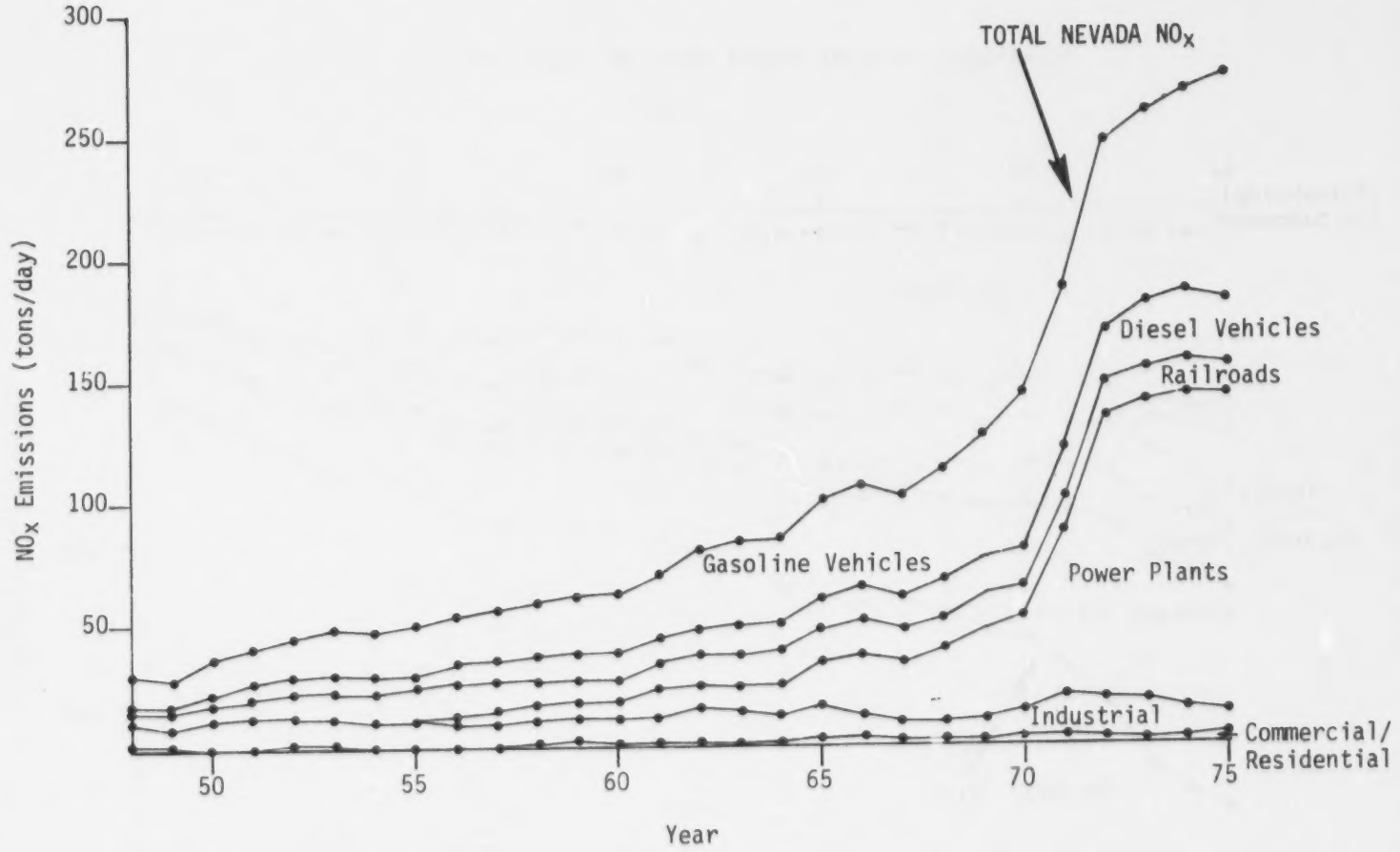


Figure 7. Nitrogen oxide emission trends in Nevada, 1948-1975.

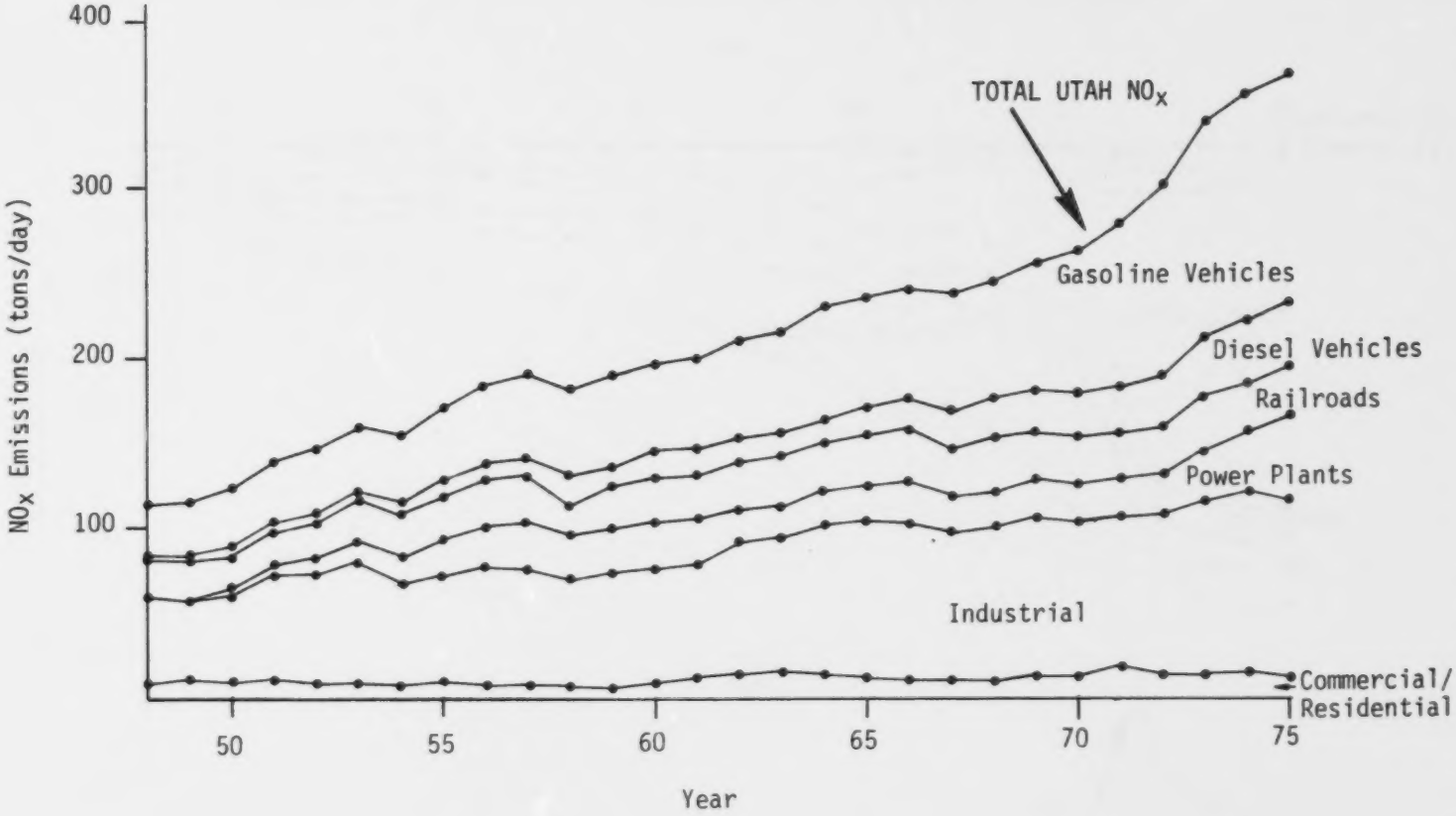


Figure 8. Nitrogen oxide emission trends in Utah, 1948-1975.

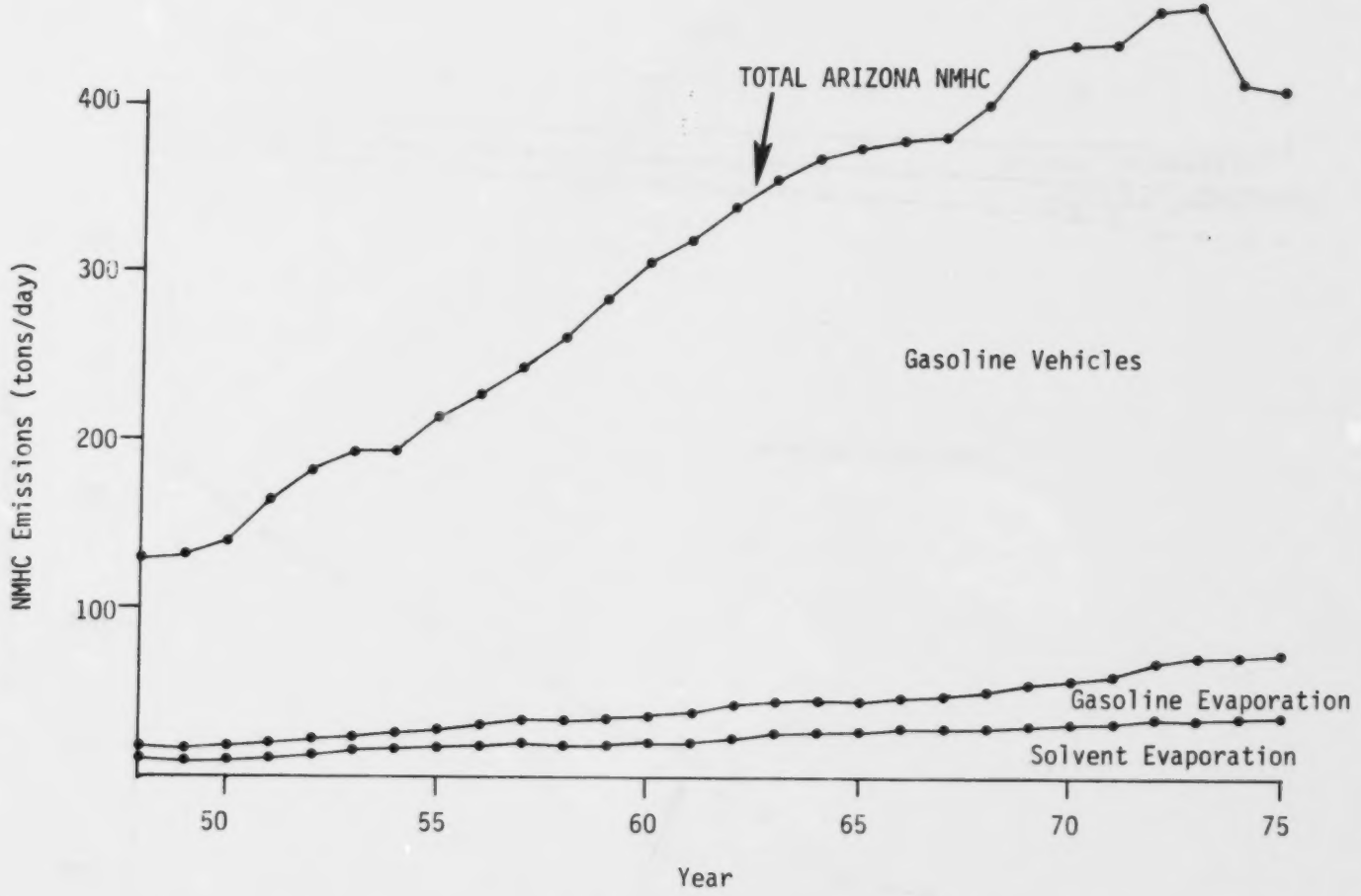


Figure 9. Nonmethane hydrocarbon emission trends in Arizona, 1948-1975.

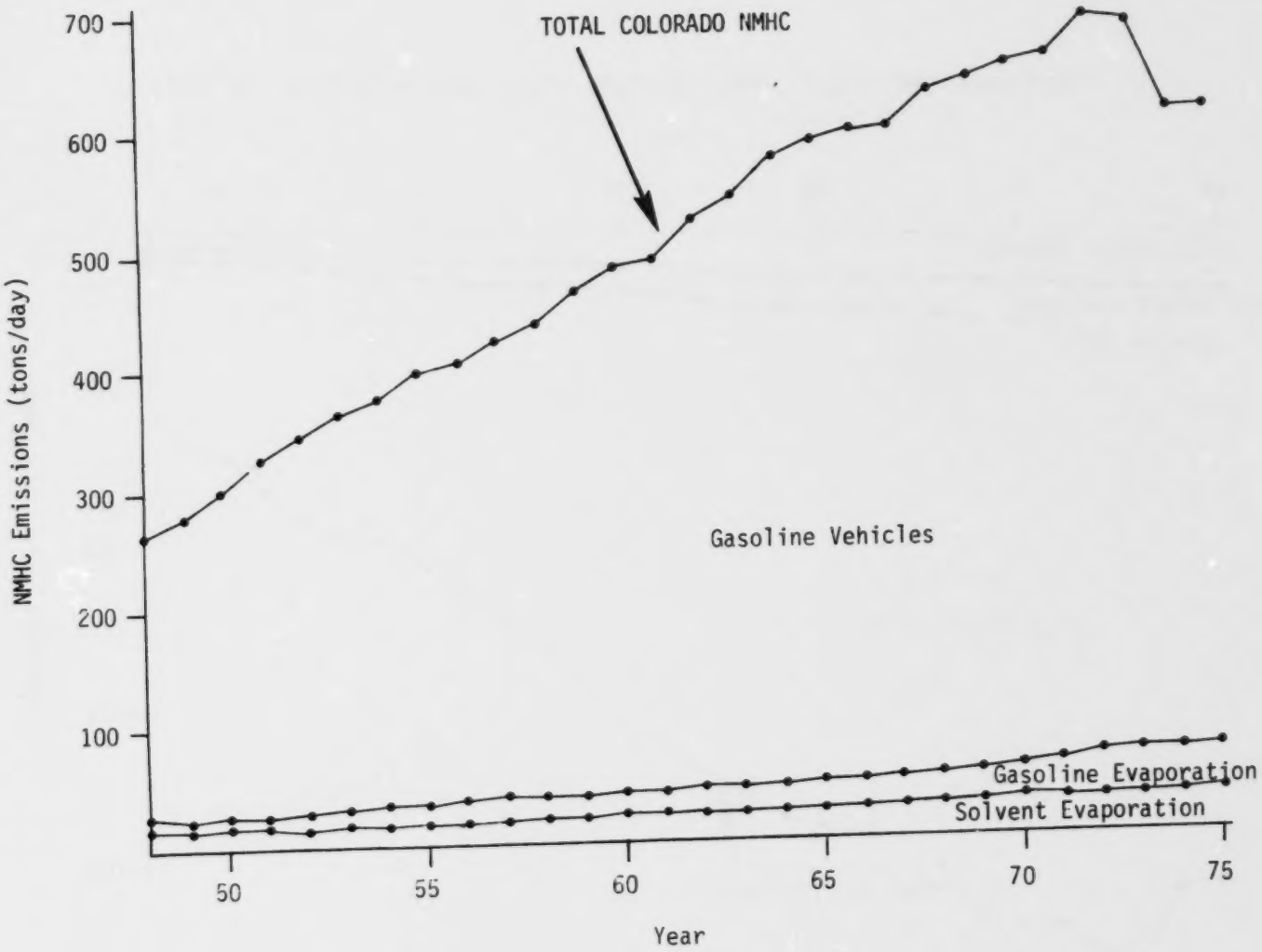


Figure 10. Nonmehtane hydrocarbon emission trends in Colorado, 1948-1975.

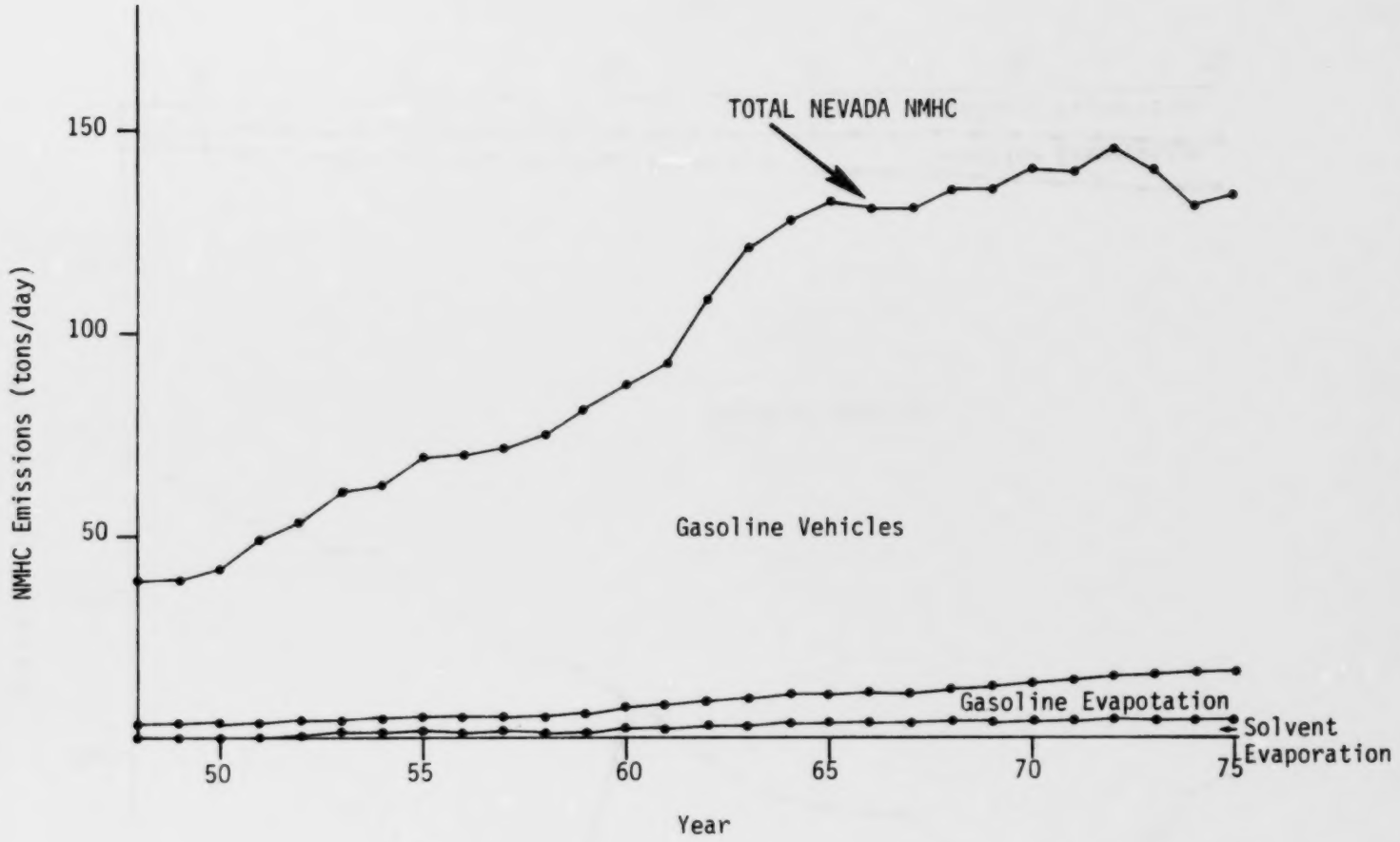


Figure 11. Nonmehtane hydrocarbon emission trends in Nevada, 1948-1975.

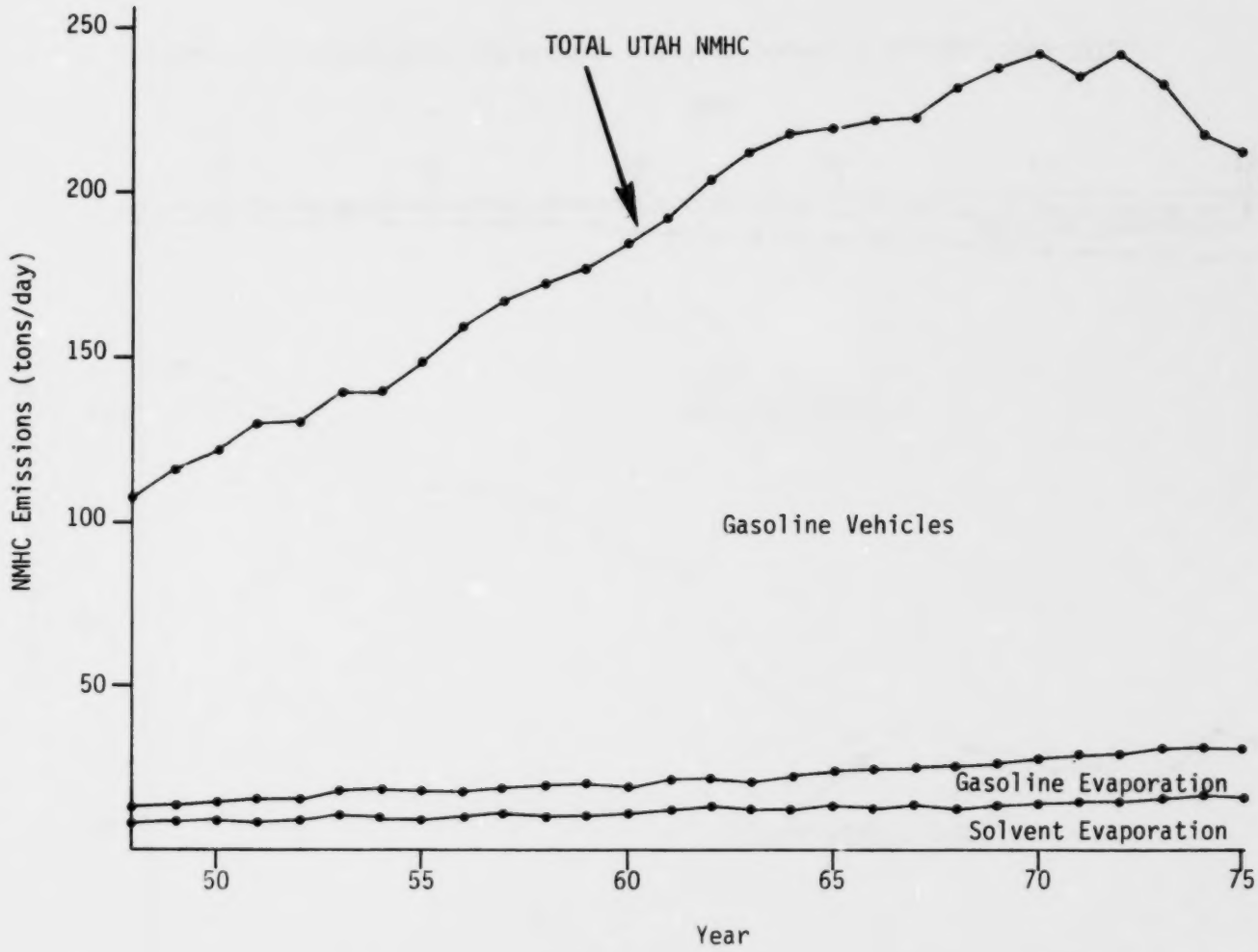


Figure 12. Nonmehtane hydrocarbon emission trends in Utah, 1948-1975.

The other significant sources of SO_x emissions in the Southwest include railroads, power plants, and industrial/commercial/residential fuel combustion. Railroading, a very substantial source of SO_x in the late 1940's, became a negligible source of SO_x by the middle 1950's as diesel locomotives were substituted for coal locomotives. Power plants have been a rapidly growing source category and now rank second to copper smelters in total Southwest SO_x emissions. SO_x emissions from industrial/commercial/residential fuel combustion have remained approximately constant over the 2½ decades, as switches to cleaner fuels (from coal and residual oil to distillate oil and gas) compensated for increased energy demand.

As shown in Figures 5 through 8, NO_x emissions climbed steadily in the four states from 1948 to 1975, increasing by a factor of 7 in Arizona and Nevada, a factor of 4 in Colorado, and a factor of 3 in Utah. The two major source categories for NO_x, power plants and gasoline vehicles, accounted for most of this rising trend. These two source categories produced a very pronounced upward trend in NO_x during the late 1960's and early 1970's due to increased electricity demand, greater coal use by utilities, traffic growth, and increased automotive NO_x emission factors (a result of the "leaning-out" of engines which was used as an initial control measure for hydrocarbons and carbon monoxide). The other significant source categories for NO_x -- industrial boilers, diesel vehicles, railroads, and commercial/residential fuel combustion -- produced, in toto, a very gradual rise in NO_x emissions which contributed slightly to the overall NO_x increase.

Figures 9 through 12 indicate that NMHC emissions in the Southwest rose steadily from the late 1940's to a peak in the early 1970's and then started to decrease. This basically reflects the trend in the dominant source category for NMHC, gasoline vehicles. Emissions rose with traffic growth for most of the period, began to level off with the automotive controls of the 1960's, and started downward as the automotive standards became more stringent in the 1970's. The especially pronounced dip in 1974 was produced in part by the "gasoline crisis" of that year.

PRIMARY SULFATE EMISSIONS

During the initial phases of this project, a special issue was brought to our attention concerning possible differences between coal-fired power plant SO_x emissions and smelter SO_x emissions with respect to sulfate and

visibility impacts. Specifically, the question was raised whether power plant SO_x emissions might be less important (per ton) to ambient sulfates and visibility than are smelter SO_x emissions because power plant emissions might contain a much smaller fraction of primary sulfates. In order to help resolve this question, we have reviewed the literature on primary sulfate emissions from power plants and have gathered data from various researchers on primary sulfate emissions from smelters. The information we obtained is presented and discussed in Appendix B. Although there are some questions concerning the various sampling methods that have been used to test smelters for primary sulfates, the existing data indicate that the fraction of primary sulfates from smelters is either about the same as, or somewhat less than, the fraction of primary sulfates from coal-fired power plants.

EMISSION TRENDS FOR INDIVIDUAL AIR BASINS

The emission trends presented in this chapter are organized by state partly because a state-to-state breakdown will be useful in later analyses, and partly because much of the underlying data for emission trends are only available on a state-to-state basis. For some of the analyses performed later in this report, it will also be necessary to have emission trends for individual Air Quality Control Regions (AQCR's). In Appendix C, we show that it is a fairly good approximation to assume that emission trends in several AQCR's are just a constant times the emission trends for the corresponding state. The factors for computing AQCR emission trends from state emission trends are presented in Appendix C.

CHAPTER 3

HISTORICAL VISIBILITY TRENDS IN THE SOUTHWEST

A previous study (Trijonis and Yuan, 1978a) included data on visibility trends at 12 locations in the Southwest. The trends were based on visibility percentiles (e.g. medians), and the study examined a time period from 1948 to 1972. This chapter updates the previous visibility trend study in two ways: (1) the time period is extended through 1976, and (2) previously unknown changes in observation locations are accounted for.

CHANGES IN OBSERVATION LOCATIONS

As part of our previous study of visibility trends in the Southwest, we conducted a survey designed to check the quality of airport data by inquiring about the visibility markers, reporting procedures, observation locations, and other factors affecting the visual range measurements. Although the survey proved very useful in many respects, there were problems with a question regarding whether the observation locations had changed "significantly" since 1948. Possibly because of the vagueness of the term "significantly", we have found that the responses sometimes did not identify all changes in location that had occurred.

We recently discovered that it is possible to obtain, from the National Climatic Center, forms which provide very detailed histories of the locations of the weather observation stations. After ordering these forms, it was determined that several changes in observation location had occurred which might affect the previous trend study. Accordingly, the trend study was performed again, accounting for all relocations in observation sites.

Before redoing the trend study, we applied statistical tests to investigate whether the changes in observation locations significantly altered reported visibility levels. Two types of test were used to estimate both the net jump in visibility produced by the relocation and the statistical significance of that jump. These two tests, a t-test on the net jump in quarterly medians and a multivariate regression test on the jump in seasonally adjusted quarterly medians, are described in Appendix D.

Table 2 lists all of the relocations that occurred at the 12 trend sites from 1948 to 1976 and summarizes the results of the statistical tests. The relocations are organized into three groups. The first group of four were accounted for in the previous visibility trend study. The second group of two were not previously accounted for, but they could not affect the major conclusion of our prior report -- that visibility had deteriorated significantly in the Southwest from the middle 1950's (1953-1955) to the early 1970's (1970-1972). The last group of five were not previously accounted for and could affect our prior conclusions.

For each statistical test, Table 2 lists the estimated net jump in median visibility (both in miles and percent), the t-statistic for the jump, and the significance level for the jump (the confidence level that the t-statistic is different from zero). Based on the estimated net percentage jump in visibility, the significance level of the jump, and the agreement between the two statistical tests, the last column of Table 2 presents our overall conclusion as to whether or not the relocation produced a significant change in reported visibilities. The conclusions are listed as either "significant", possibly significant", or "apparently not significant".

Because of limitations in the statistical tests and associated uncertainties concerning the real significance of the relocations, we have decided to adopt the following policy throughout this report: For those sites where the relocation produced a "significant" change in reported visibilities, the data will be restricted to a period excluding the relocation (e.g. Phoenix from 1959 to 1976). For those sites where the change is "possibly significant" or "apparently not significant", the analysis will always be done twice -- once restricted to a period excluding the relocation (e.g. Prescott from 1948 to 1969), and once including all available data (e.g. Prescott from 1948 to 1976).

HISTORICAL VISIBILITY TRENDS

Figures 13 through 24 summarize historical visibility trends at the 12 study sites considered in our previous report (Trijonis and Yuan, 1978a). All site relocations, as well as our qualitative conclusions concerning the significance of those relocations, are noted in the Figures. Also noted are

TABLE 2. ANALYSIS OF THE STATISTICAL SIGNIFICANCE OF OBSERVATION SITE RELOCATIONS ON REPORTED AIRPORT VISIBILITIES.

STATION	MONTH MOVED	DISTANCE MOVED (miles)	t-TEST ON JUMP IN QUARTERLY MEDIANS*				REGRESSION TEST ON JUMP IN SEASONALLY ADJUSTED QUARTERLY MEDIANS*				CONCLUSION
			Net Jump in Visibility (miles)	(percent)	t Value for Jump	Significance level of t Value	Net Jump in Visibility (miles)	(percent)	t Value for Jump	Significance level of t Value	
Phoenix, AZ	12/52	0.8	-1.7	-5%	1.8		-3.6	-10%	3.9	>99%	Significant
Phoenix, AZ	5/58	0.3	+6.8	+18%	5.6	>99%	+3.8	+10%	3.6	>99%	Significant
Colorado Springs, CO	4/67	1.1	+14.1	+17%	1.1		+11.5	+14%	3.7	>99%	Significant
Pueblo, CO	9/69	0.1	+4.9	+6%	3.0	>95%	+5.5	+7%	2.1	>95%	Significant
Winslow, AZ	5/74	0.2	-12.9	-23%	1.5		-38.6	-69%	4.0	>99%	Significant
Grand Junction, CO	2/50	0.1	+1.6	+2%	0.1		+0.5	+1%	0.1		Apparently N Significant
Prescott, AZ	2/70	0.3	+19.3	+29%	1.1		+6.4	+10%	0.6		Possibly Significant
Tucson, AZ	10/58	0.9	-1.3	-2%	0.4		+2.4	+3%	1.7		Apparently N Significant
Denver, CO	5/69	1.7	+1.3	+2%	0.5		-7.4	-14%	6.9	>99%	Possibly Significant
Ely, NV	9/61	0.1	-8.1	-25%	1.6		-4.6	-14%	0.8		Possibly Significant
Salt Lake City, UT	7/54	0.1	-4.7	-20%	1.3		-14.3	-59%	5.8	>99%	Significant

*The analysis is performed with median visibilities except for the following: Winslow (80th percentile), Prescott (75th percentile), and Ely (90th percentile).

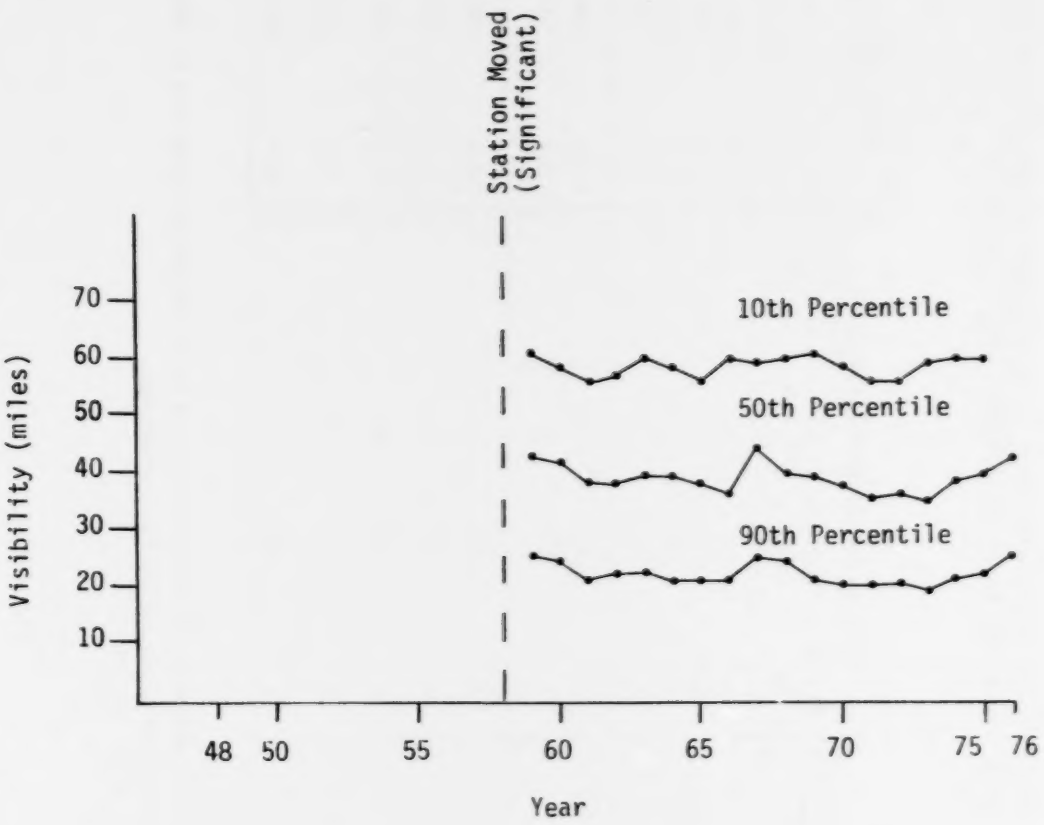


Figure 13. Long-term visibility trends at Phoenix.

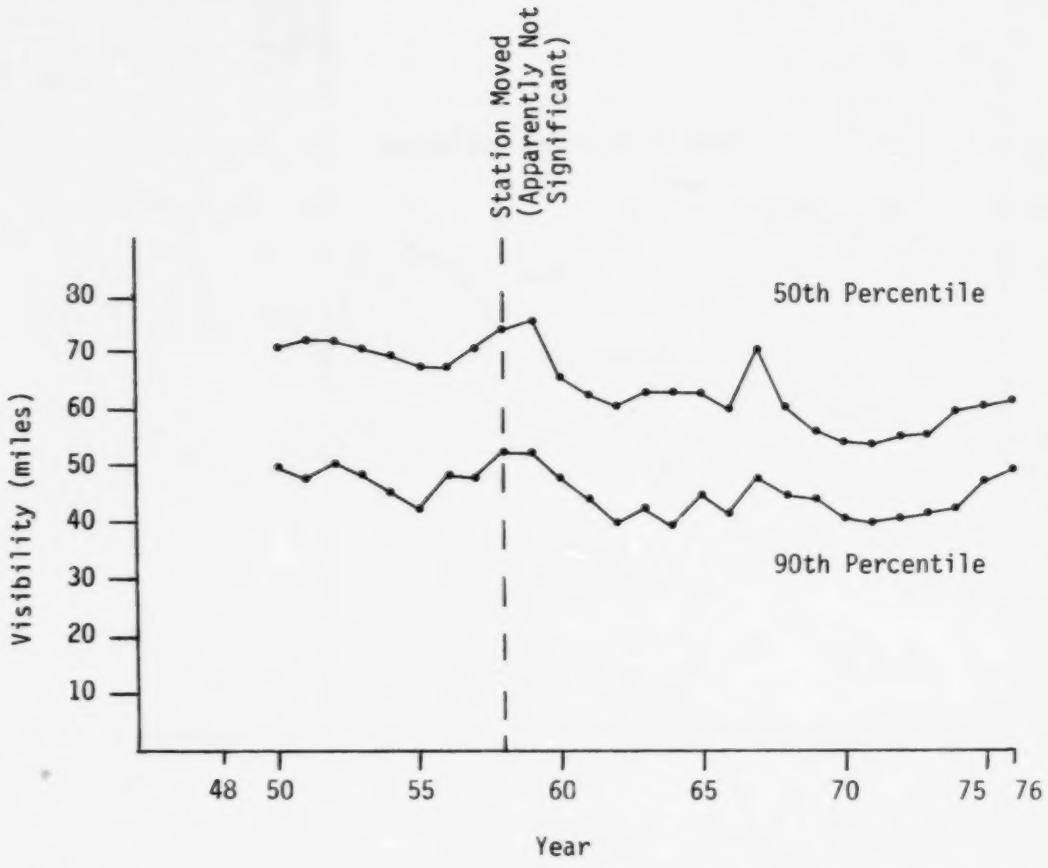


Figure 14. Long-term visibility trends at Tucson.

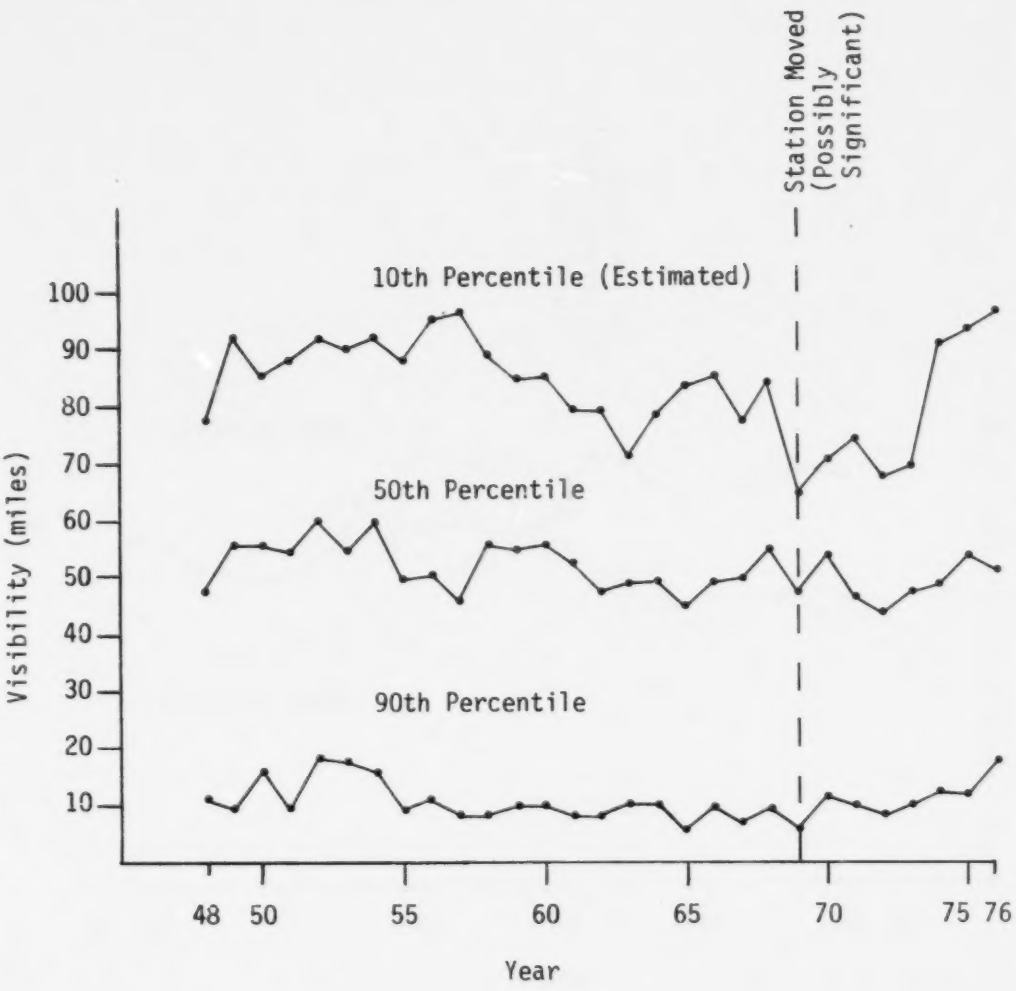


Figure 15. Long-term visibility trends at Denver.

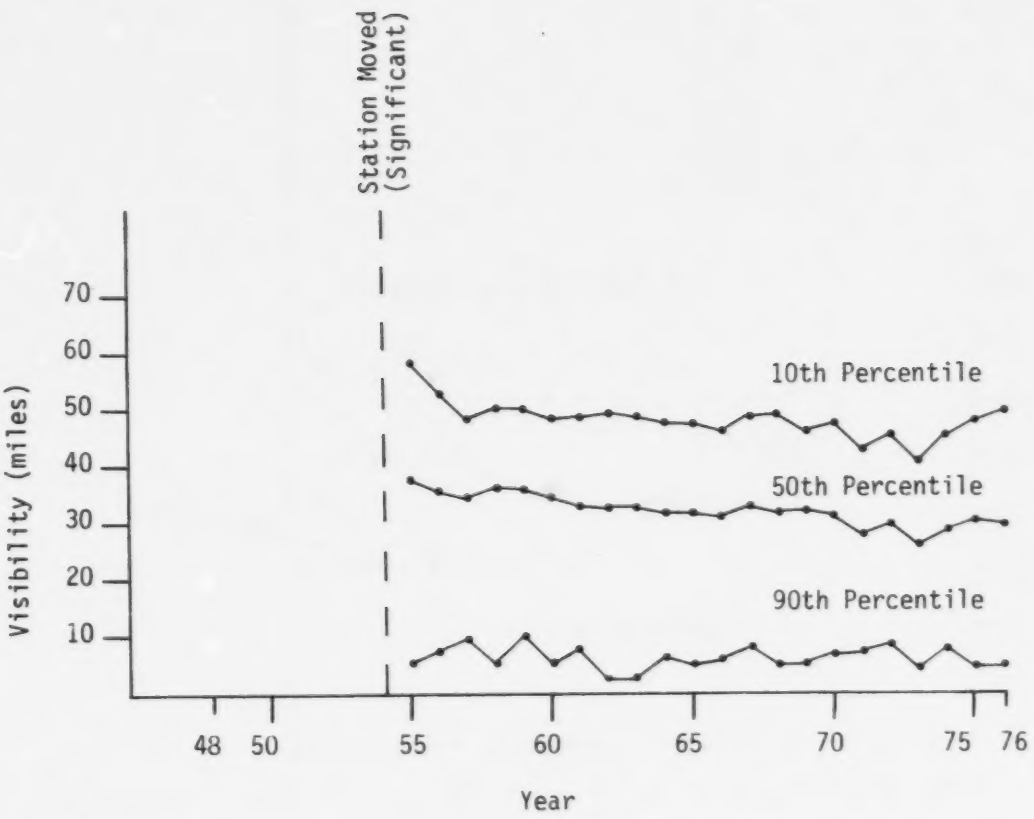


Figure 16. Long-term visibility trends in Salt Lake City.

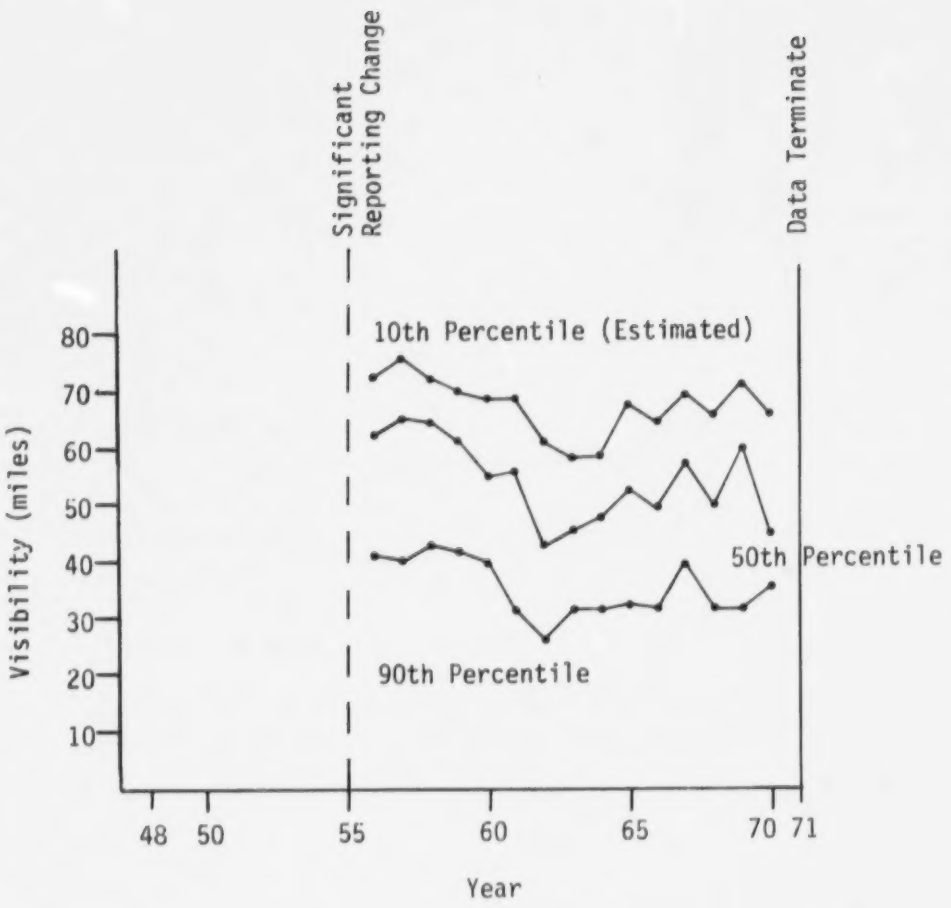


Figure 17. Long-term visibility trends at Fort Huachuca.

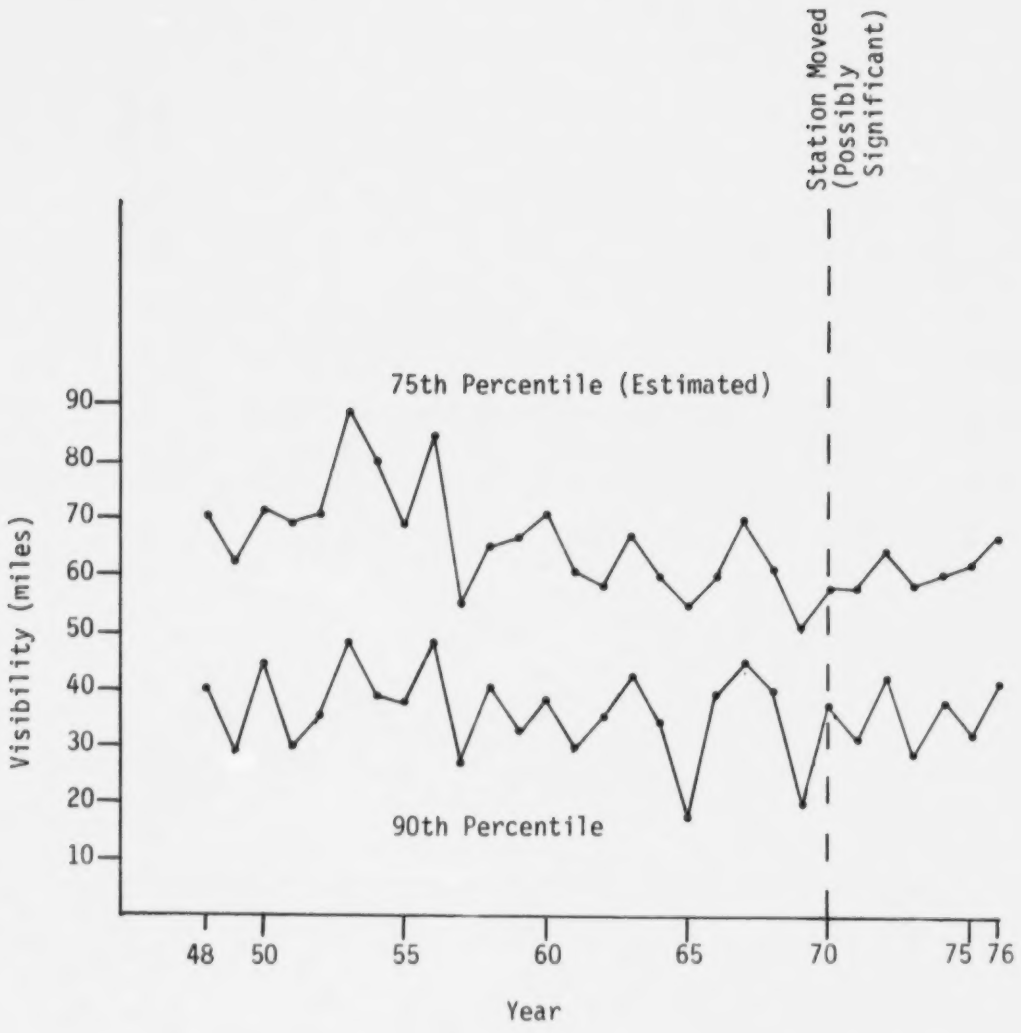


Figure 18. Long-term visibility trends at Prescott.

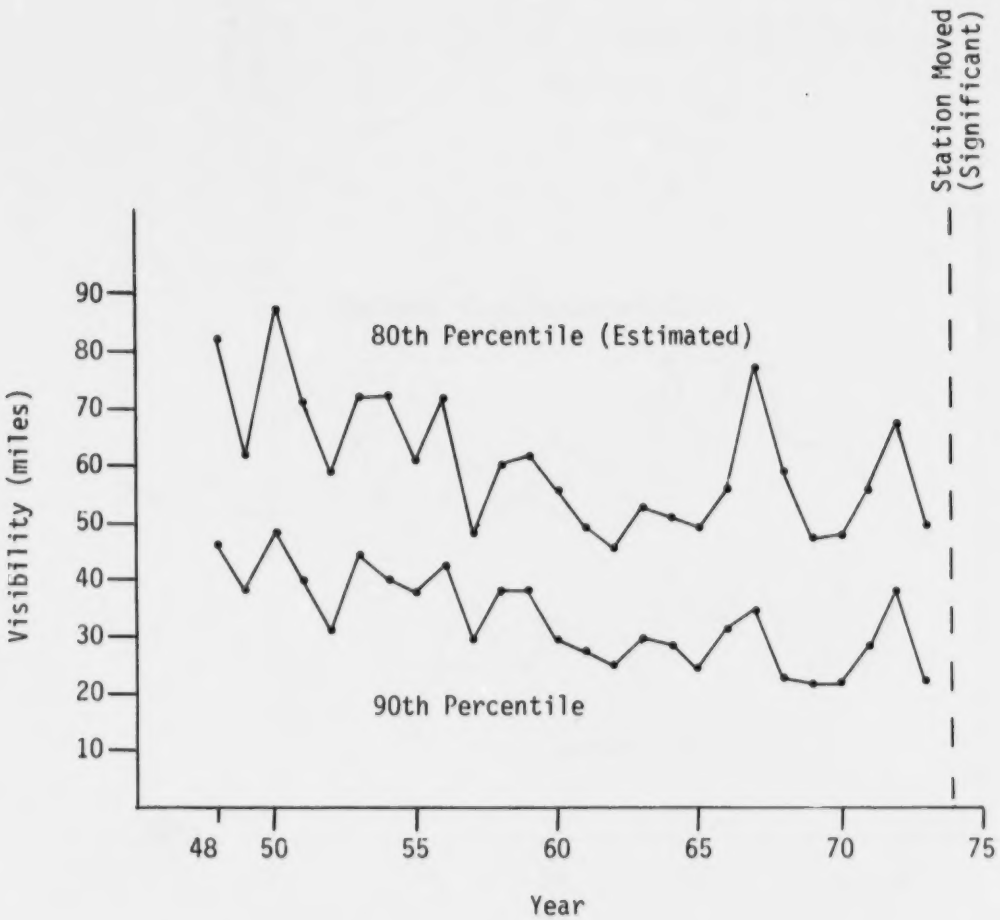


Figure 19. Long-term visibility trends at Winslow.

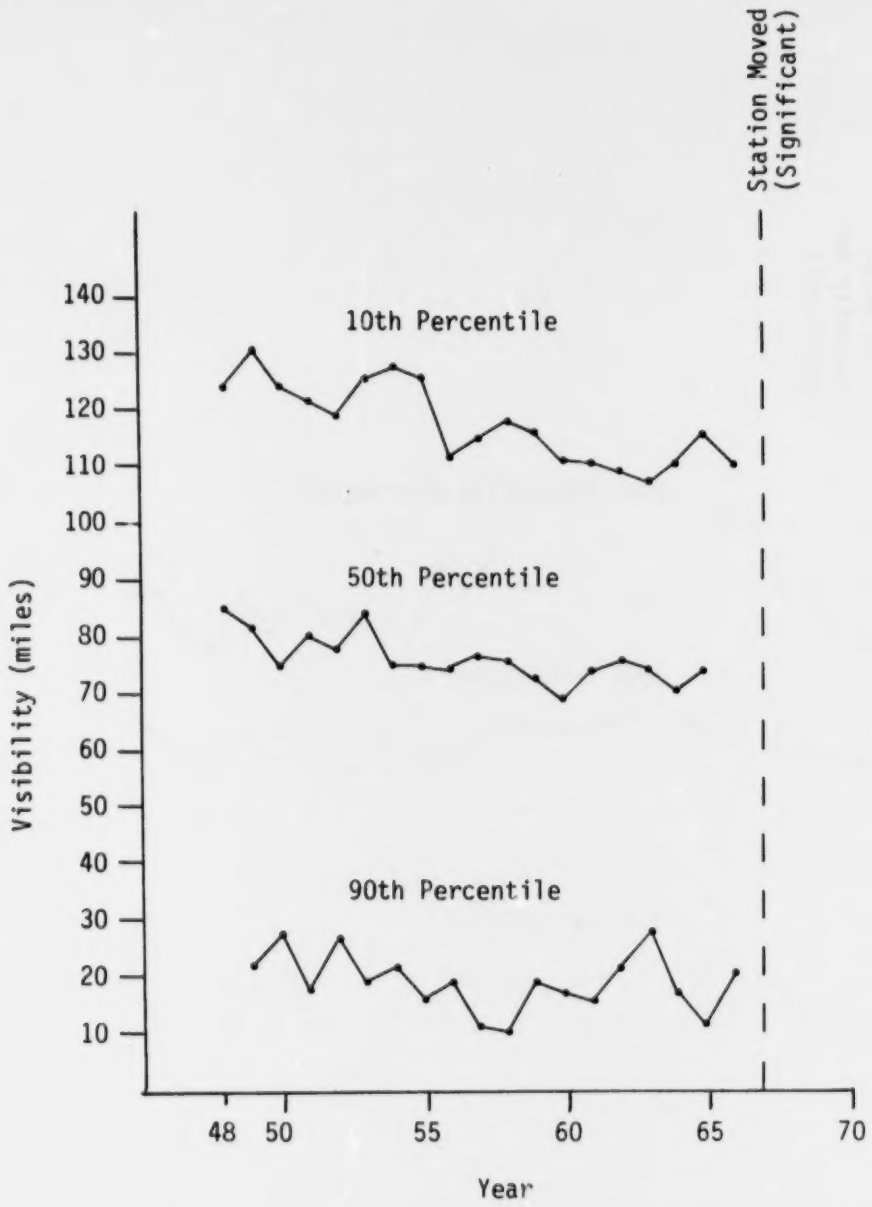


Figure 20. Long-term visibility trends at Colorado Springs.

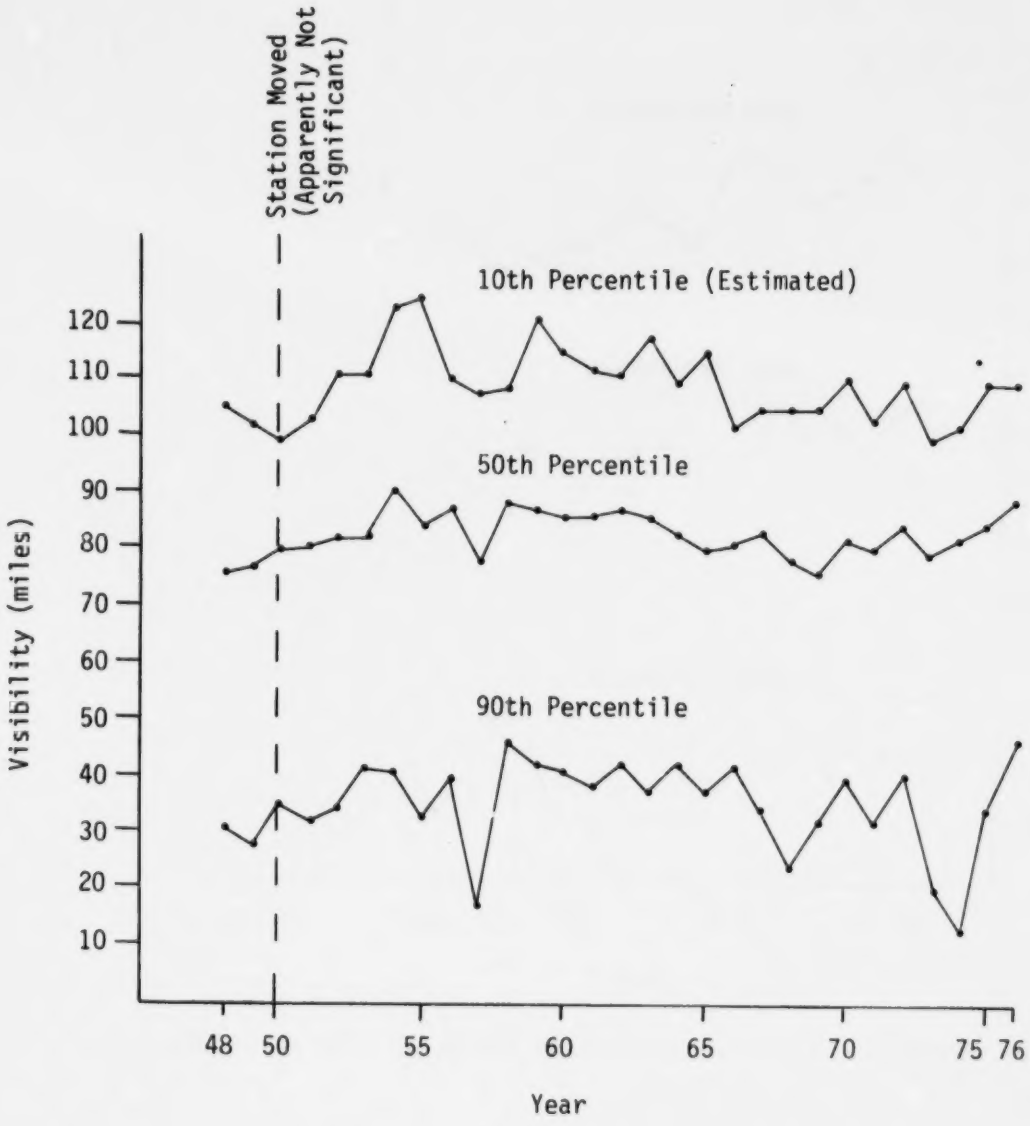


Figure 21. Long-term visibility trends at Grand Junction.

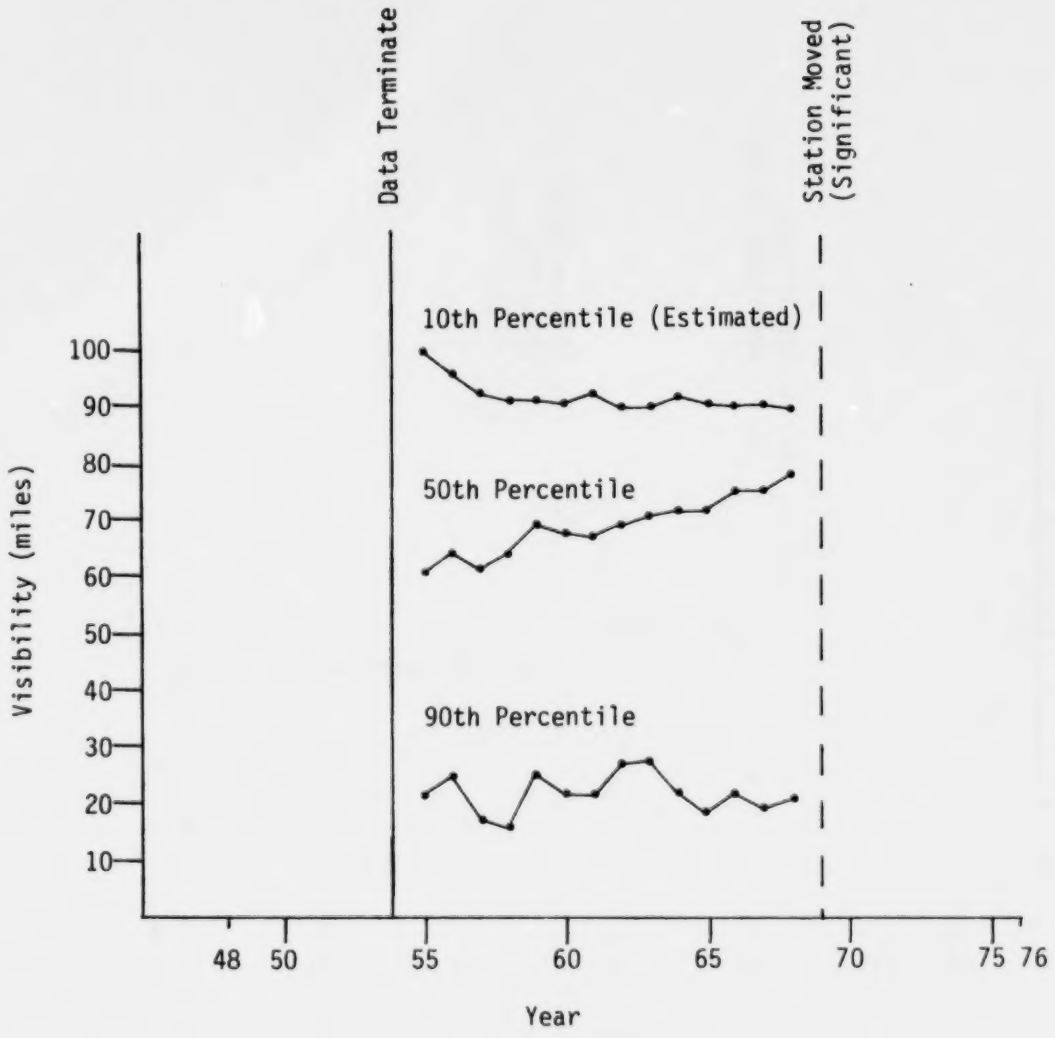


Figure 22. Long-term visibility trends at Pueblo.

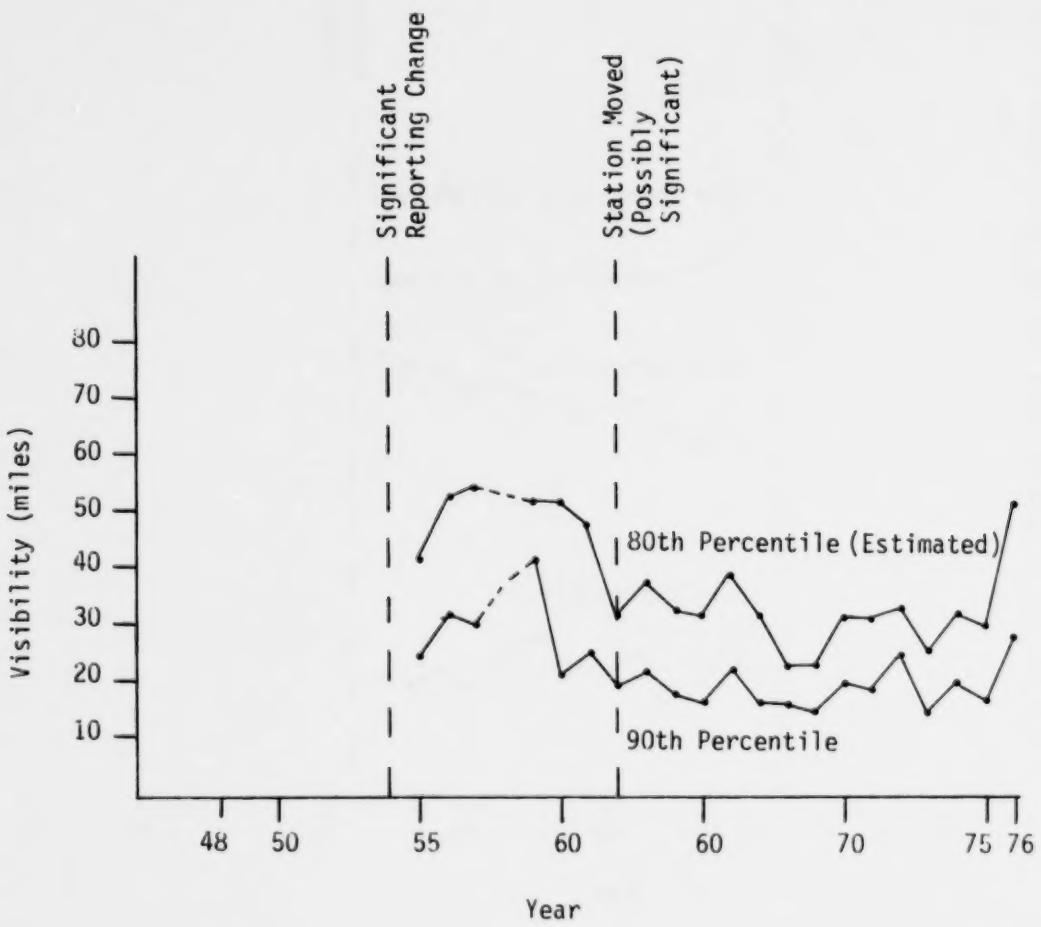


Figure 23. Long-term visibility trends at Ely.

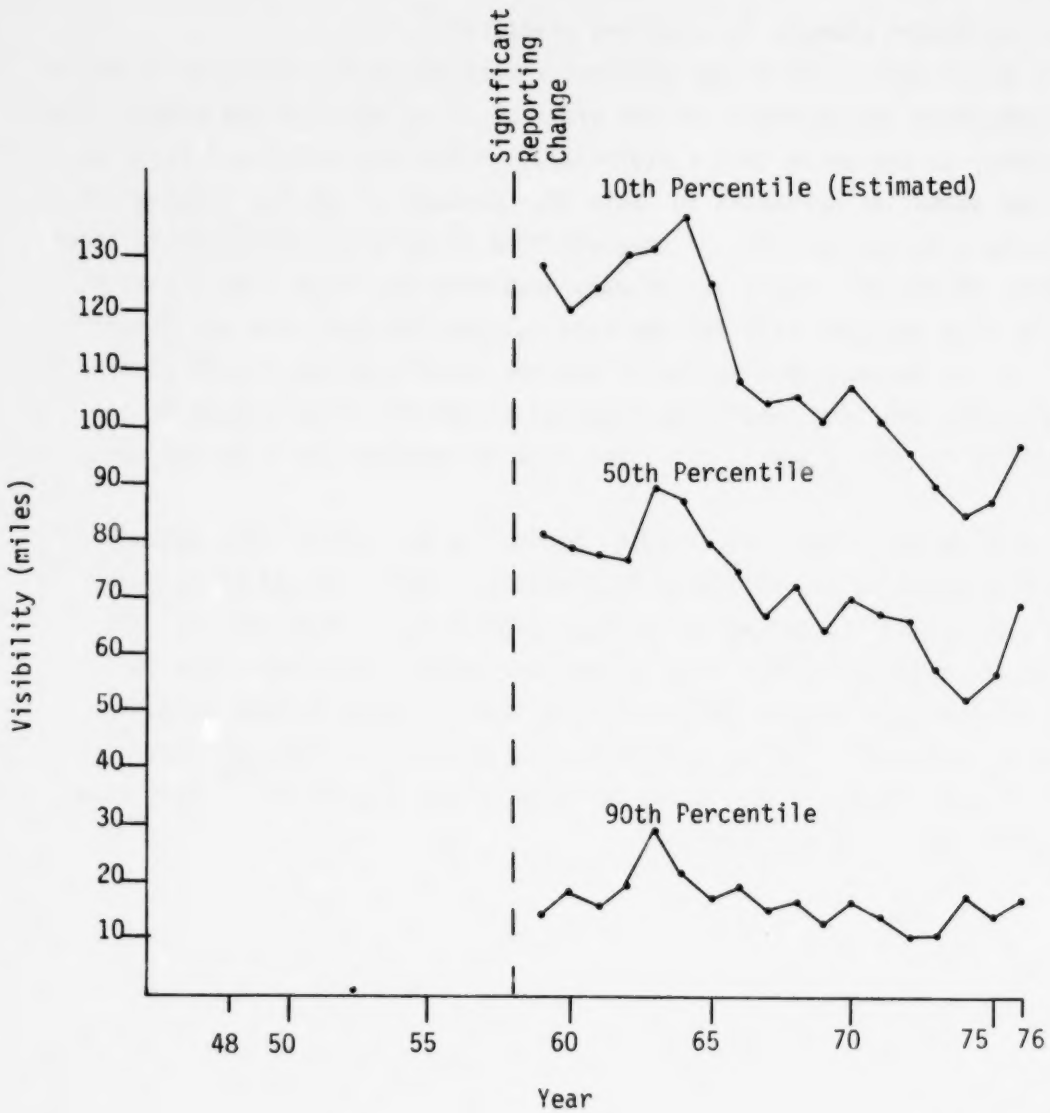


Figure 24. Long-term visibility trends at Cheyenne.

three significant changes in reporting practices.*

A major conclusion of our previous report was that visibility deteriorated throughout the Southwest on the order of 10 to 30% from the middle 1950's (1953-1955) to the early 1970's (1970-1972). This conclusion was based on the trend summaries presented in Table 3A. Because of the new information concerning site relocations, we have modified these trend summaries as shown in Tables 3B and 3C. Table 3B includes data only for fixed site locations; Table 3C also includes data for the site relocations that were not "significant". It is obvious that whichever way one calculates the trends (Table 3B or Table 3C), the same conclusion remains: visibility deteriorated on the order of 10 to 30% at nearly all sites from the middle 1950's to the early 1970's.

Examing data from 1948 to 1970, Latimer et al. (1978) also noted a decreasing trend in visibility at Southwestern sites. In addition, they found that visibility tended to increase significantly from 1970 to 1976. Our results tend to confirm this latter conclusion; the eight sites for which we have data through 1976 exhibited the following changes in median visibility from 1970-1972 to 1974-1976: Phoenix (+12%), Prescott (+7%)**, Tucson (+12%), Denver (+7%), Grand Junction (+3%), Ely (+18%)***, Salt Lake City (0%), and Cheyenne (-12%).

---

*These three changes occurred at Fort Huachuca (causing a downward jump in visibility from 1955 to 1956), Ely (causing a downward jump in visibility from 1954 to 1955), and Cheyenne (causing an upward jump in visibility from 1958 to 1959). The trends for these sites are started after the reporting changes.

**75 th percentile instead of median.

***80 th percentile instead of median.

TABLE 3A. NET PERCENT CHANGES IN VISIBILITY, 1953-1955 TO 1970-1972, ORIGNIAL ANALYSIS (TRIJONIS AND YUAN, 1978a)

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 TO 1971		
	Best (10th %) Visibility	Median Visibility	Worst (90th %) Visibility
URBAN			
Phoenix, AZ†	0%	-23%	-20%
Tucson, AZ	N.A.	-22%	-11%
Denver, CO	-22%	-13%	-29%
Salt Lake City, UT	-24%	-27%	-19%
NONURBAN			
Fort Huachuca, AZ†	-12%	-27%	-28%
Prescott, AZ	N.A.	-25%*	-21%
Winslow, AZ	N.A.	-17%**	-27%
Colorado Springs, CO†	-17%	-12%	-17%
Grand Junction, CO	-9%	-4%	-3%
Pueblo, CO†	-9%	+35%	0%
Ely, NV†	N.A.	-42%**	-33%
Cheyenne, WY†	-28%	-23%	-19%

N.A. Not available

†Trends for these sites are extrapolated from data covering most, but not all, of the period 1954-1971.

*75th percentile visibility instead of median visibility.

**80th percentile visibility instead of median visibility.

TABLE 3B. NET PERCENT CHANGES IN VISIBILITY, 1953-1955 TO 1970-1972, ALL SITE RELOCATIONS DISCOUNTED

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 TO 1971		
	Best (10th%) Visibility	Median Visibility	Worst (90th%) Visibility
URBAN			
Phoenix, AZ†	0%	-23%	-20%
Tucson, AZ†	N.A.	-32%	-24%
Denver, CO†	-12%	- 8%	-50%
Salt Lake City, UT†	-17%	-22%	+ 3%
NONURBAN			
Fort Huachuca, AZ†	-12%	-27%	-28%
Prescott, AZ†	N.A.	-28%*	-18%
Winslow, AZ	N.A.	-17%**	-27%
Colorado Springs, CO†	-17%	-12%	-17%
Grand Junction, CO	- 9%	- 4%	- 3%
Pueblo, CO†	-11%	+34%	- 5%
Ely, NV†	N.A.	-13%**	+10%
Cheyenne, WY†	-28%	-23%	-19%

N.A. Not available

† Trends for these sites are extrapolated from data covering most, but not all, of the period 1954-1971. The periods for trend analysis at these sites are as follows: Phoenix, 1959-1972 (site moved in 1958); Tucson, 1959-1972 (site moved in 1958); Denver, 1953-1968 (site moved in 1969); Salt Lake City, 1955-1972 (site moved in 1954); Fort Huachuca, 1956-1970 (reporting practices change in 1955, data terminate in 1971): Prescott, 1953-1969 (site moved in 1970); Colorado Springs, 1953-1966 (site moved in 1967); Pueblo, 1955-1968 (data start in 1954, site moved in 1969); Ely, 1962-1972 (site moved in 1961); and Cheyenne, 1959-1972 (reporting practices change in 1958).

* 75th percentile visibility instead of median visibility.

** 80th percentile visibility instead of median visibility.

TABLE 3C. NET PERCENT CHANGES IN VISIBILITY 1953-1955 TO 1970-1972, ALL SIGNIFICANT SITE RELOCATIONS DISCOUNTED

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 TO 1971		
	Best (10th%) Visibility	Median Visibility	Worst (90th%) Visibility
URBAN			
Phoenix, AZ†	0%	-23%	-20%
Tucson, AZ	N.A.	-22%	-11%
Denver, CO	-22%	-13%	-29%
Salt Lake City UT†	-17%	-22%	+ 3%
NONURBAN			
Fort Huachuca, AZ†	-12%	-27%	-28%
Prescott, AZ	N.A.	-25%*	-21%
Winslow, AZ	N.A.	-17%**	-27%
Colorado Springs, CO†	-17%	-12%	-17%
Grand Junction, CO	- 9%	- 4%	- 3%
Pueblo, CO†	-11%	+34%	- 5%
Ely, NV†	N.A.	-42%	-33%
Cheyenne, WY†	-28%	-23%	-19%

N.A. Not available

†Trends for these sites are extrapolated from data covering most, but not all, of the period 1954-1971. The periods for trend analysis at these sites are as follows: Phoenix, 1959-1972 (site moved in 1958); Salt Lake City, 1955-1972 (site moved in 1954); Fort Huachuca, 1956-1970 (reporting practices change in 1955, data terminate in 1971); Colorado Springs, 1953-1966 (site moved in 1967); Pueblo, 1955-1968 (data start in 1954, site moved in 1969); Ely, 1955-1972 (reporting practices change in 1954); and Cheyenne, 1959-1972 (reporting practices change in 1958).

*75th percentile instead of median visibility.

**80th percentile instead of median visibility.

CHAPTER 4

REGIONAL EXTINCTION/EMISSION COEFFICIENTS BASED ON THE 1967-1968 COPPER STRIKE

The nine month copper strike of 1967-1968 produced a very large reduction of sulfur oxide emissions in the Southwest.* Compared to average daily emission levels during surrounding years (1965, 1966, 1969, 1970, and the other 15 months of 1967-1968), sulfur oxide emissions dropped 5550 TPD in southeast Arizona, 700 TPD at McGill (Nevada), and 580 TPD at Magna (Utah). By relating these SO_x emission reductions to corresponding air quality changes, this chapter estimates regional extinction/emission coefficients for sulfur oxides in the Southwest.

METHODOLOGY

Our previous report (Trijonis and Yuan, 1978a) documented airport visibility changes and NASN** Hi-Vol sulfate changes at the sites shown in Figure 25 during the 1967-1968 nine month copper strike. That report discussed in detail the large percentage improvements in air quality during the copper strike (e.g. visibility improved 8-29% at the 5 airports in Arizona, and sulfates dropped 60-67% at the 4 NASN sites in Arizona), the high statistical significance of the observed improvements, and evidence that meteorological variation did not contribute significantly to the improvement. For the purposes of the present study -- derivation of empirical extinction/emission coefficients -- the air quality change of interest during the strike is the <u>absolute</u> change in the extinction coefficient (B), with units of $[10^4 m]^{-1}$. This can be readily derived from the airport data using the Koschmeider relationship,

$$B = \frac{24.3}{V} , \qquad (1)$$

where V is the median visibility in [miles]. The change in absolute

*The overall SO_x reduction in the four study states (Arizona, Colorado, Nevada, and Utah) was 95%. If we also include New Mexico, the overall reduction was 91%.

**National Air Surveillance Network

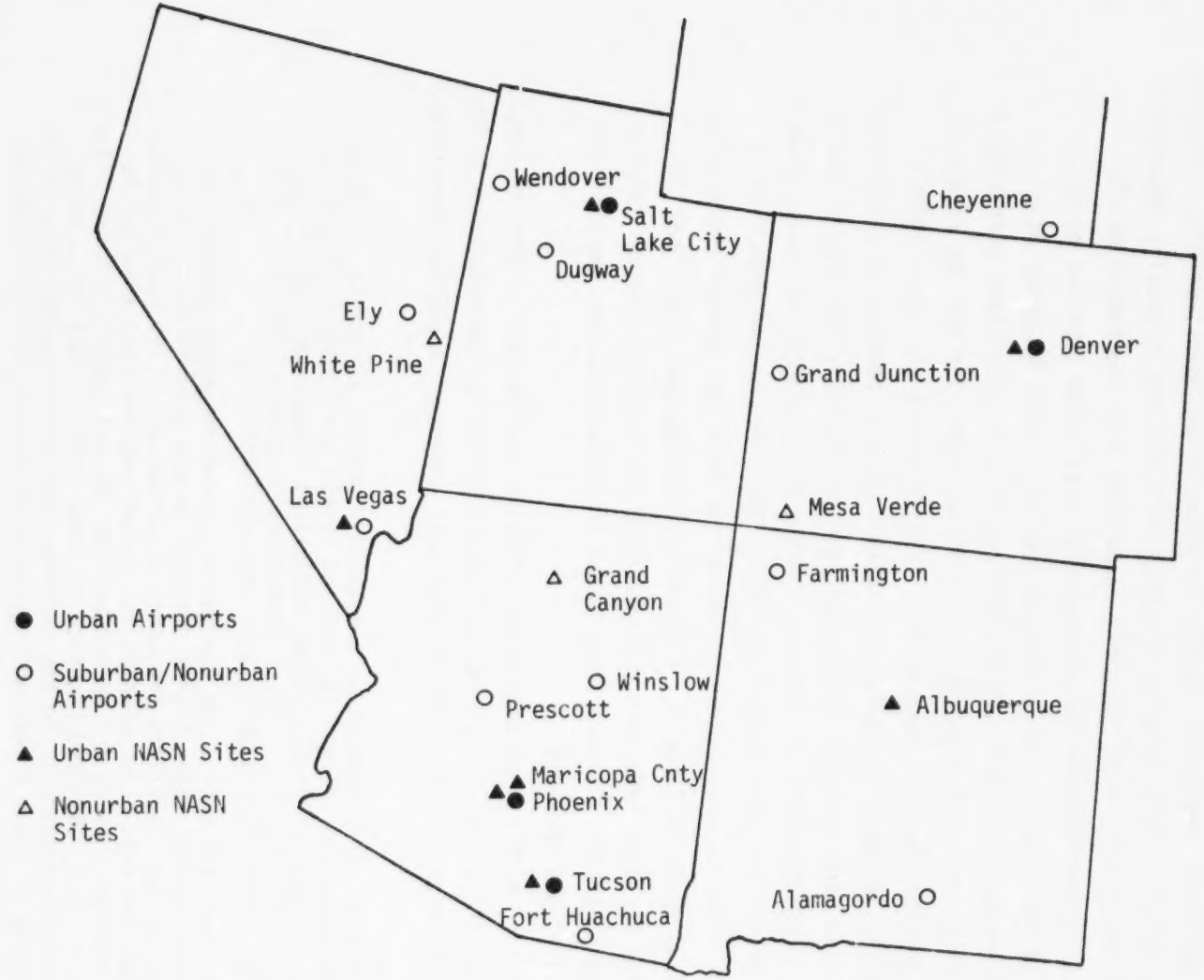


Figure 25. Airport weather stations and NASN monitoring sites used to determine air quality changes during the 1967-1968 copper strike.

extinction can also be estimated from ambient sulfate data by assuming an extinction coefficient per unit mass for sulfates. For this purpose, we have chosen an extinction coefficient per unit mass of .04 $(10^4 m)^{-1}/(\mu g/m^3)$ based on empirical regression models for Phoenix and Salt Lake City (Trijonis and Yuan, 1978a). This value is slightly less than the typically reported values of .06 $(\pm .03)(10^4 m)^{-1}/(\mu g/m^3)$ calculated from the theory of Mie scattering for aerosols in the accumulation size range (Latimer et al., 1978; White and Roberts, 1977; Ursenbach et al., 1978; Waggoner et al., 1976). However, a value of .04 $(10^4 m)^{-1}/(\mu g/m^3)$ is consistent with theoretical predictions for the Southwest, if one accounts for the low relative humidity in that area (Latimer et al., 1978; Trijonis and Yuan, 1978a).

Figures 26 and 27 present seasonally adjusted* changes in extinction** (airport data) and sulfates (NASN data) during the 1967-1968 copper strike. In order to relate these air quality changes to emissions, we have chosen -- based on prevailing wind directions (NOAA, 1977) and on the proximity of monitoring sites to smelters -- to couple the emission sources and monitoring sites as shown in Table 4. Alamogordo, Albuquerque, Grand Junction, Denver, and Cheyenne have been excluded from the analysis because they appear to be less likely impact areas based on distance to the smelters and prevailing wind directions.

For each airport, an extinction/emission coefficient is derived simply by dividing the extinction change during the strike by the reduction in SO_x emissions from the smelters paired with that airport. A similar computation

---

* Seasonally adjusted changes in air quality during the strike are determined by comparing average (or median) levels during the strike to average (or median) levels during equivalent 9 month periods of surrounding years (usually 6 years symmetrically around 1967-1968, but sometimes fewer years depending on data availability).

** In most cases the extinction changes are based on median visibility levels, but in some cases higher percentiles are used to avoid extrapolation of the visibility frequency distributions. The reader should note that the extinction changes for Denver and Prescott turn out to be the same whether or not we account for the relocation of those sites (Denver in June, 1969 and Prescott in June, 1970). That is -- using six surrounding years to do the seasonal adjustment happens to give the same result as using 2 surrounding years for Denver and 4 surrounding years for Prescott.

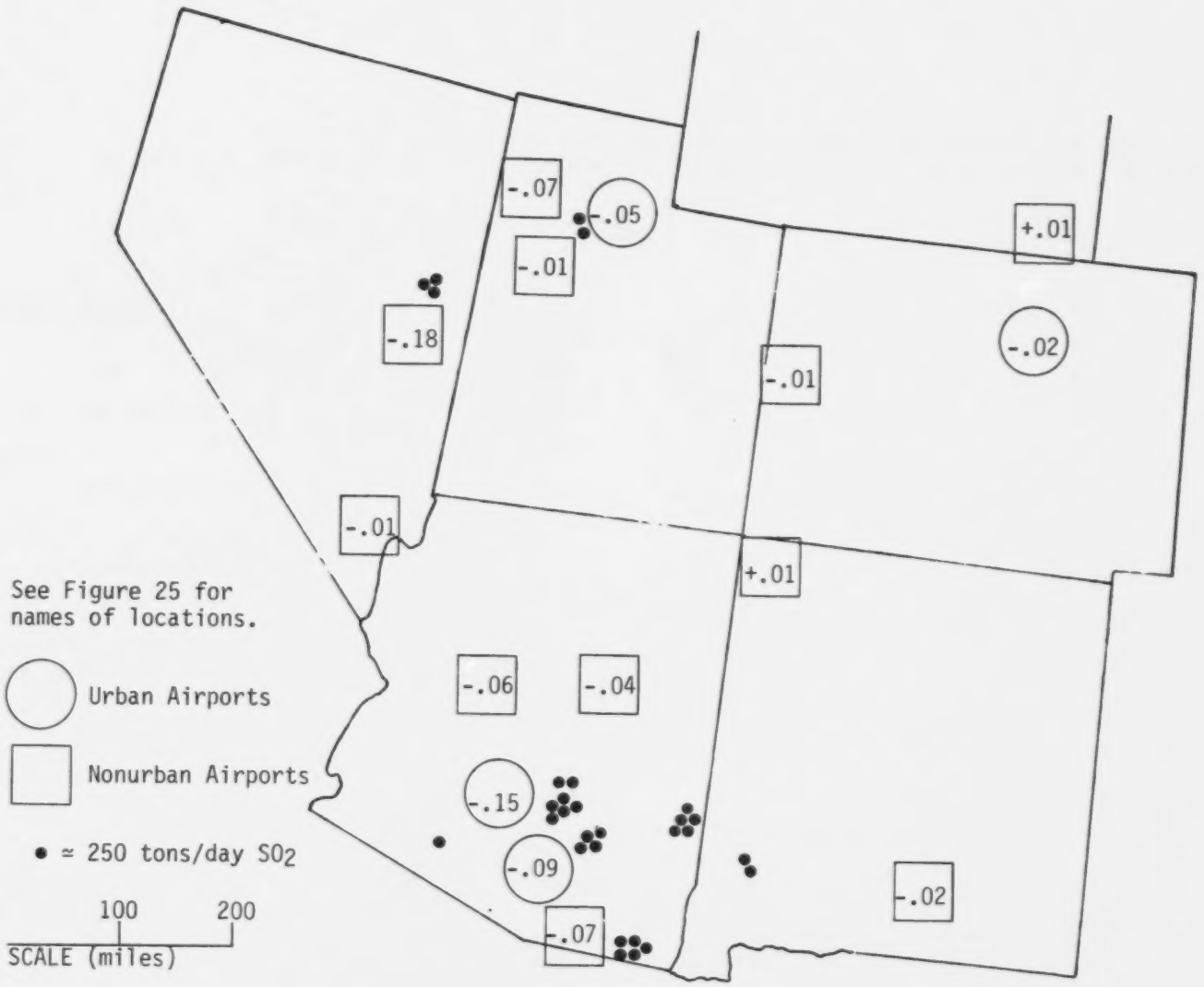


Figure 26. Seasonally adjusted changes in extinction during the copper strike, units of $[10^4 \text{ meters}]^{-1}$, compared to the geographical distribution of smelter SO_x emissions.

Figure 27. Seasonally adjusted changes in sulfate during the copper strike, units of $\mu g/m^3$, compared to the geographical distribution of smelter SO_x emissions.

TABLE 4. PAIRING OF AIRPORTS AND NASN SITES WITH SMELTERS MOST LIKELY TO AFFECT THOSE SITES.

EMISSION SOURCE	AIRPORTS	NASN SITES
Arizona Smelters	Fort Huachuca, Tucson, Phoenix, Prescott, Winslow, Farmington, and Las Vegas	Tucson, Phoenix, Maricopa County, Grand Canyon, Mesa Verde, and Las Vegas
McGill, NV Smelter	Ely, Wendover, and Dugway*	White Pine
Magna, UT Smelter	Salt Lake City and Dugway*	Salt Lake City

*Because of uncertainty concerning the source most likely to affect Dugway, Dugway has been coupled with both the McGill and Magna smelters.

is made with the NASN sulfate data. The SO_x extinction/emission coefficients based on the airport data may be overestimated because of simultaneous reductions in primary particulates from smelters during the copper strike. Based on light scattering contributions from sulfate and fine silicon particles reported by Macias et al (1979) for nonurban areas and a smelter plume, we conclude that the overestimate may be on the order of 10-30%.

The above analysis neglects superposition of effects from the three smelter areas. It is probably safe to neglect superposition in considering sites paired with the Arizona smelters; however, because of the extremely large emissions of the Arizona smelters, it may not be accurate to neglect their impact on sites paired with the McGill and Magna smelters. The consequences of this possible source of error will be addressed in the next section which presents the results of our analysis.

EXTINCTION/EMISSION COEFFICIENTS FOR SO_x

Figure 28 presents the extinction/emission coefficients based on visibility changes during the copper strike. Change in extinction divided by change in SO_x emissions is plotted as a function of the distance between the airport and the associated smelters. For those airports paired with the Arizona smelters, a weighted average distance (by emissions) is used.

Figure 29 presents changes in sulfate divided by changes in emissions, plotted as a function of distance between the NASN sites and the smelters. Figure 30 is a composite of Figures 28 and 29, with sulfates converted to extinction using a factor of .04 $(10^4 m)^{-1}/(\mu g/m^3)$. Figure 30 indicates that the extinction/emission coefficients based on the airport visibility data agree fairly well with the extinction/emission coefficients based on the NASN sulfate data. At distances of 50 to 200 miles from the smelters, both data sets consistently yield extinction/emission coefficients on the order of .01 to .03 $(10^4 m)^{-1}/(1000\ TPD\ SO_x)$.* Also, both data sets seem to imply that the extinction/emission coefficient rises considerably as the distance to the source decreases from 50 to 10 miles. The only major disagreement

*The only exception to this conclusion among the 11 sites in the 50 to 200 mile range is the Wendover airport data.

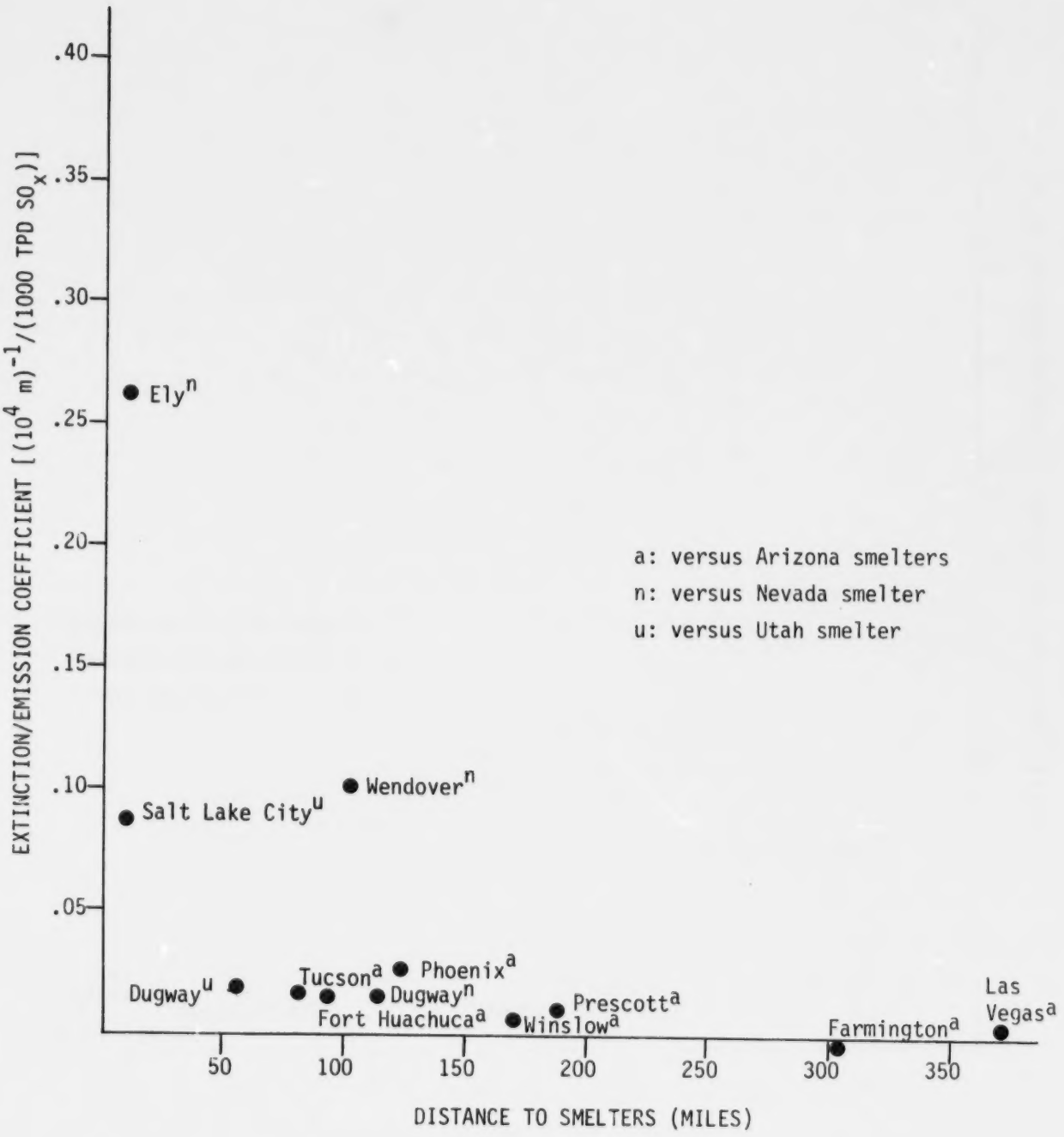


Figure 28. Extinction/emission coefficients based on airport data during the 1967-1968 copper strike.

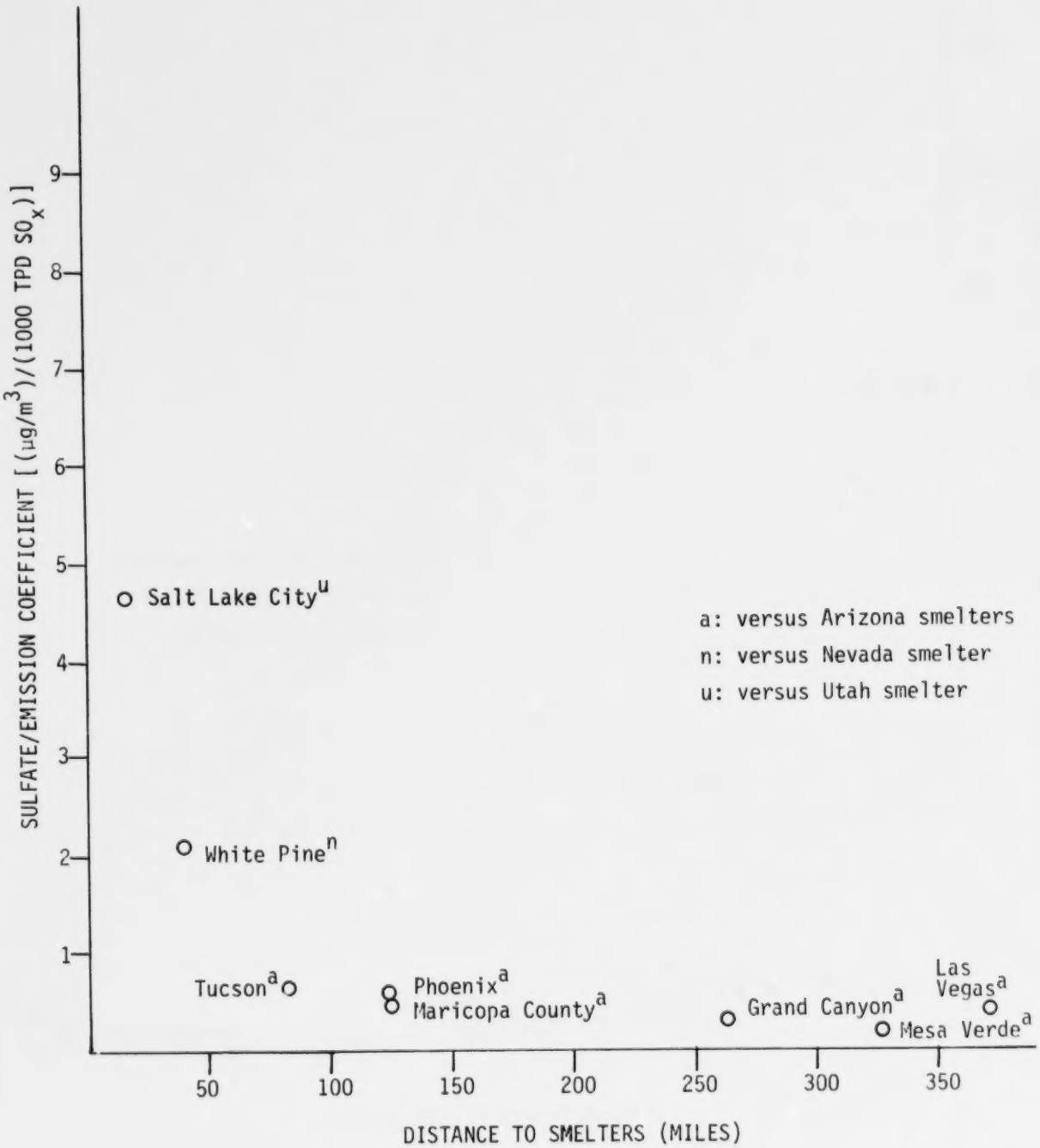


Figure 29. Sulfate/emission coefficients based on NASN data during the 1967-1968 copper strike.

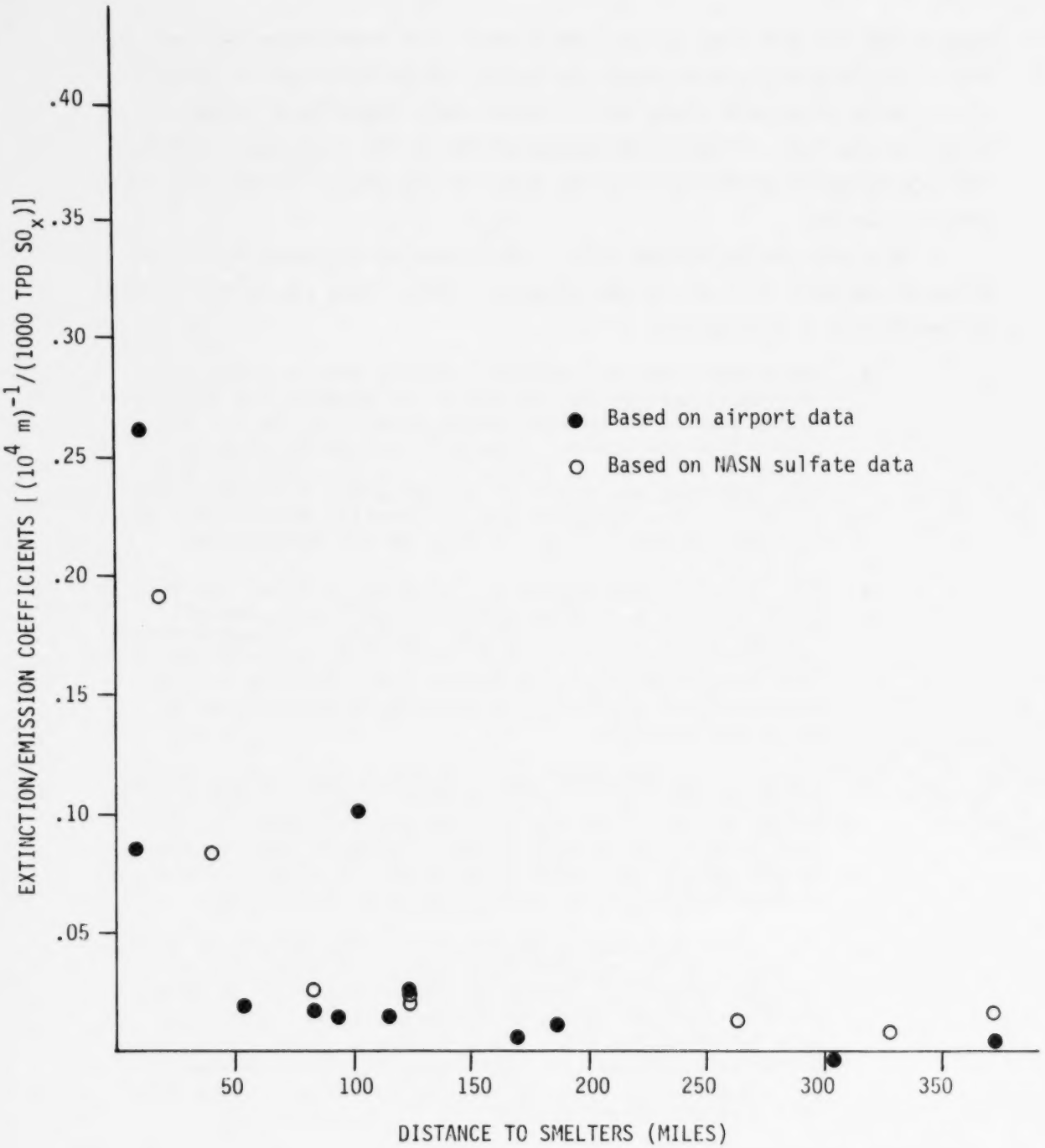


Figure 30. Extinction/emission coefficients from airport and NASN data during the 1967-1968 copper strike.

between the two data sets is that the airport data (Farmington and Las Vegas) indicate negligible changes in extinction at distances of 300-375 miles, while three NASN sites imply statistically significant changes (Trijonis and Yuan, 1978a) at distances of 250 to 375 miles and yield extinction/emission coefficients on the order of .01 $(10^4 m)^{-1}/(1000\ TPD)$ at those distances.

The higher extinction/emission coefficients at distances within 40 miles of smelters deserves further comment. This effect can be due to any of the factors listed below:

- The larger extinction/emission coefficients at sites near individual smelters may be due to the tendency for air pollution sources to produce greater effects at smaller distances from the source. Figure 31 replots the data in Figure 30 on a log-log scale; the log-log regression line indicates that the effect of SO_x emissions on regional extinction in the Southwest may be inversely proportional to the distance from the source (i.e. an x^{-1} dependence).

- The sites that are nearest to individual smelters and that yield the high extinction/emission coefficients are all coupled with the Utah and Nevada smelters. The extinction/emission coefficients at these sites might be artificially high because we have neglected emissions from the Arizona smelters which might produce significant impacts even at very long distances.

- The extinction/emission coefficients at the Utah and Nevada sites are more sensitive to potential errors in estimates of the extinction changes because we are dividing by much smaller emission changes. Relatively small absolute errors in the extinction data at these sites can produce rather large errors in the extinction/emission coefficients.

- The extinction/emission coefficients might tend to be slightly higher at the northern Utah and Nevada sites because relative humidity is higher at those locations. Relative humidity averages 50-60% in northern Utah and Nevada but only 30-50% at the other study locations (NOAA, 1977). Higher relative humidity could tend to produce greater sulfate formation rates as well as greater extinction per unit mass of ambient sulfates.

It is tempting to attribute most or all of the increased extinction/emission coefficients at the northern Utah and Nevada locations to the closer proximity of the smelters (i.e. the x^{-1} dependence). However, because of the

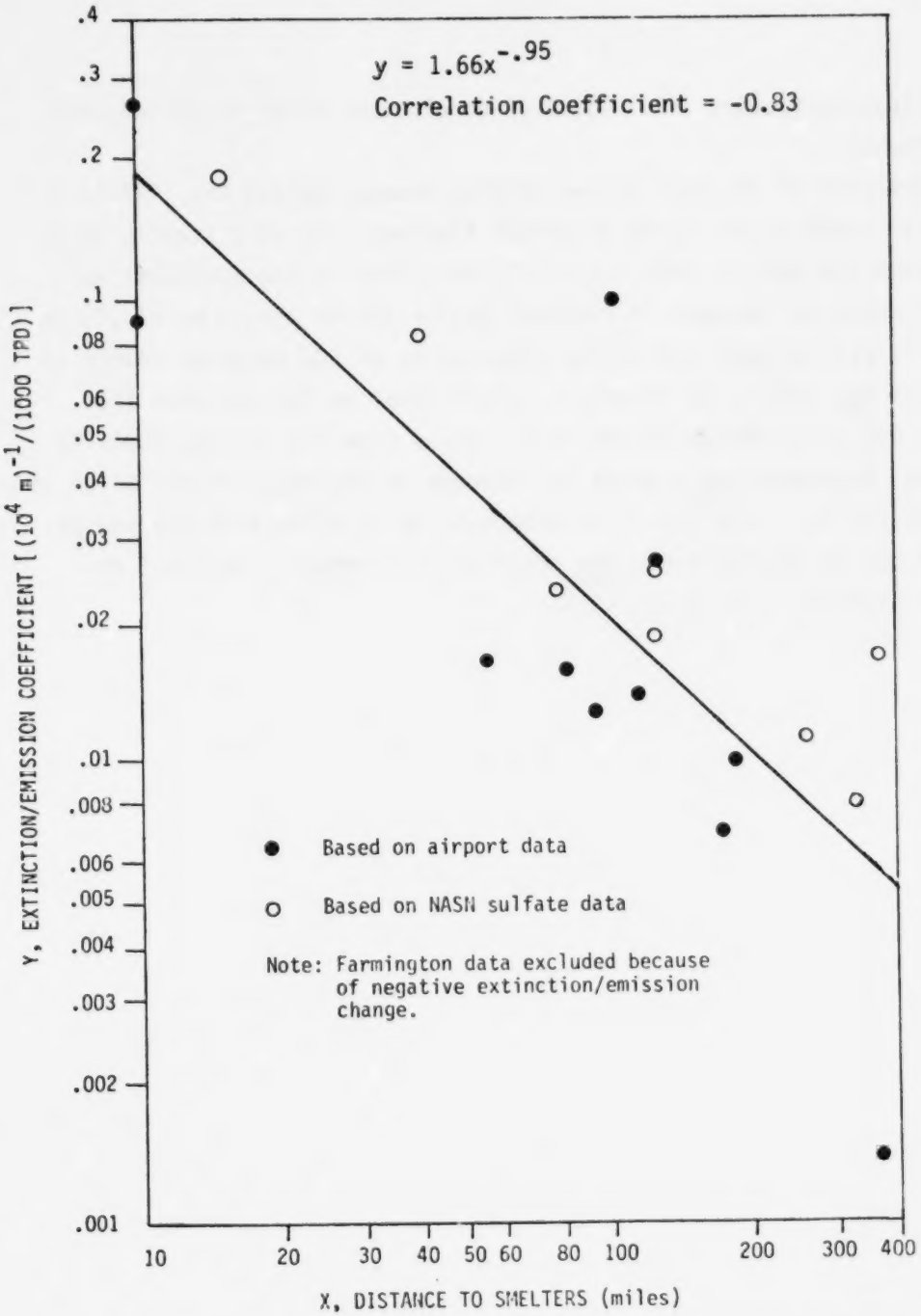


Figure 31. Log-log plot of extinction/emission coefficient versus distance to smelter.

other complicating factors involved, this conclusion cannot be stated with great confidence.

Our analysis of emission and extinction changes during the 1967-1968 copper strike leads to following principal findings: (1) at distances 50 to 200 miles from the source, 1000 TPD of SO_x emissions in the Southwest apparently produces an increase in regional extinction on the order of .01 to .03 $(10^4 m)^{-1}$; (2) regional extinction produced by an SO_x emission source in the Southwest may tend to be inversely proportional to the distance from the source; (3) at distances of 250 to 375 miles from the source, 1000 TPD of SO_x in the Southwest may produce an increase in regional extinction on the order of .01 $(10^4 m)^{-1}$; and (4) at distances 10 to 15 miles from the source, 1000 TPD of SO_x in the Southwest may produce an increase in regional extinction as high as .1 to .25 $(10^4 m)^{-1}$.

CHAPTER 5

REGIONAL EXTINCTION/EMISSION COEFFICIENTS BASED ON HISTORICAL EMISSION CHANGES FROM 1948 TO 1975

As demonstrated in Chapter 2, large changes in SO_x, NO_x, and NMHC emissions have occurred in the Southwest over the period 1948 to 1975. This chapter attempts to derive regional extinction/emission coefficients by relating the historical emission changes to corresponding visibility changes through a correlation/regression analysis.

METHODOLOGY

The basic methodology of this chapter is to regress yearly values of median extinction (based on airport data) against yearly emission levels from 1948 to 1975. Multiple linear regressions are run of the form

$$B = a + c_1 SO_x + c_2 NO_x + c_3 NMHC \qquad (1)$$

where the units of extinction (B) are $[10^4 \text{ meters}]^{-1}$, and the units of emissions are 1000 TPD. The emission variables are usually chosen as statewide totals or AQCR totals (which are adjusted statewide values, see Appendix C), but sometimes we also use multi-state emission totals or emissions of individual source types (e.g. copper smelters). The regressions are run step-wise, retaining only those coefficients that are greater than zero at a 95% significance level. The regression coefficients, c_i, represent extinction/emission coefficients with units of $[(10^4 \text{ m})^{-1}/(1000 \text{ TPD})]$.

There are several limitations to our historical regression analysis. One very important drawback is the intercorrelation that exists among the "independent" variables (see Table 5); we are faced with the classical problem that everything correlates with everything. The high intercorrelations and limited number of data points (at most 28 years) make it an insurmountable problem to weed out, with certainty, the individual impacts of all three emission variables (SO_x, NO_x, and NMHC).

A second important drawback is the omission of primary particulate emissions from the analysis. Macias et al (1979) found that, in nonurban areas of the Southwest, approximately ¼ of the aerosol light scattering is presently due to primary fine silicon, while approximately ½ is due to

TABLE 5. INTERCORRELATION AMONG STATEWIDE TOTAL EMISSION TRENDS, 1948-1975

	ARIZONA			COLORADO		
	SO_X	NO_X	NMHC	SO_X	NO_X	NMHC
SO_X	1.00	0.78	0.91	1.00	0.49	0.15
NO_X		1.00	0.86		1.00	0.87
NMHC			1.00			1.00

	NEVADA			UTAH		
	SO_X	NO_X	NMHC	SO_X	NO_X	NMHC
SO_X	1.00	0.76	0.72	1.00	-0.68	-0.81
NO_X		1.00	0.77		1.00	0.85
NMHC			1.00			1.00

sulfates. Because of the apparently significant contribution from primary particles, and because of possibly important intercorrelations between primary particulate trends and gaseous precursor trends, it would be worthwhile to expand our analysis to include primary aerosols when adequate data become available (see discussion at the end of Chapter 1). If primary aerosol emission trends are highly intercorrelated with the gaseous precursor trends, the extinction/emission coefficients derived in this chapter would tend to be somewhat overestimated.

Another significant limitation is that our linear regression form neglects nonlinear interactions and synergistic effects among the three precursor emissions. It is well known that photochemical smog depends on NO_X and NMHC emissions in a rather complicated, nonlinear manner. Also, the visibility impacts of SO_X may depend on the level of the photochemical precursors (NO_X and NMHC), because photochemical oxidant can be an important factor governing the conversion of SO_2 to sulfate. For the same reason, the visibility impacts of changes in the photochemical precursors may depend on the existing SO_X level. A statistical analysis of 28 yearly data points cannot hope

to provide a complete characterization of these nonlinear and synergistic effects.

Other limitations include errors in the data base, i.e. variations in the visibility data (produced by weather fluctuations or unaccounted for changes in observation procedures) and possible errors in our emission trend estimates. Uncertainty is also introduced in the process of attempting to select the appropriate emission source area to be linked with each set of visibility data.

Despite the potentially severe drawbacks in the analysis, we will proceed with the regression study for eight visibility trend sites. The interpretation of the results will be guided by physical reasoning and the limitations of the method will be borne in mind. Although we cannot hope to derive definitive extinction/emission coefficients for SO_x, NO_x, and NMHC on various spatial scales, the analysis should help to identify the emissions that are most significant to visibility in various areas and may yield approximate estimates of the extinction attributable to those emissions.

The eight trend sites selected for the regression study are Tucson, Phoenix, Prescott, and Winslow in Arizona; the large metropolitan areas of Denver and Salt Lake City in the northern part of the study area; and two non-metropolitan sites (Grand Junction and Ely) in the northern part of the study area. Cheyenne was excluded because it is not within the four study states; Fort Huachuca, Colorado Springs, and Pueblo were excluded because they had limited time periods of continuous data that did not extend into the 1970's. With the exception of Prescott (75th percentile), Winslow (80th percentile), and Ely (90th percentile), the yearly extinction values are all based on median visibilities. Whenever a site relocation occurred that was "apparently not significant" or "possibly significant" (see Chapter 3), the regression analysis was performed twice -- both for the entire time period and for a sub-period excluding data possibly affected by the relocation.

REGRESSION ANALYSIS FOR ARIZONA SITES

The regression analysis for Arizona involves six data sets: Tuscon (1950-1975), Tuscon (1959-1975), Phoenix (1959-1975), Winslow (1948-1973), Prescott (1948-1975), and Prescott (1948-1969). Tuscon and Prescott are considered twice because of site relocations (see Chapter 3). The emission variables considered in the analysis include total Arizona SO_x, Arizona

smelter SO_X, Arizona non-smelter SO_X, total Arizona NO_X, and total Arizona NMHC.*

Table 6 summarizes the correlation coefficients between historical extinction levels and corresponding emission levels. It is noteworthy that all six data sets correlate best with total Arizona SO_X and Arizona smelter SO_X. The correlations are especially strong at Tucson and Phoenix. The results in Table 6 appear to be consistent with the finding in Chapter 2 that the copper smelters have historically been the overwhelming source of secondary aerosol precursors in Arizona. In fact, if we hypothesize that smelter SO_X emission trends were the basic cause of the extinction trends, the correlation (or lack of correlation) between extinction and the other emission variables might be partly explained as artifacts of the intercorrelation of smelter SO_X with those other emission variables (.999 with total Arizona SO_X, -.31 with non-smelter SO_X, .71 with Arizona NO_X, and .89 with Arizona NMHC).

TABLE 6. HISTORICAL EXTINCTION-EMISSION CORRELATIONS FOR ARIZONA TREND SITES

	CORRELATION COEFFICIENTS				
DATA SET	Arizona SO_X	Arizona Smelter SO_X	Arizona Non-Smelter SO_X	Arizona NO_X	Arizona NMHC
Tucson (1950-1975)	.92	.91	.03	.74	.85
Tuscon (1959-1975)	.89	.88	.10	.54	.83
Phoenix (1959-1975)	.82	.81	-.01	.37	.55
Winslow (1948-1973)	.67	.68	-.48	.49	.59
Prescott (1948-1975)	.70	.70	-.12	.49	.63
Prescott (1948-1969)	.71	.70	-.25	.59	.59

Stepwise multiple regressions of extinction versus Arizona smelter SO_X, Arizona non-smelter SO_X, Arizona NO_X, and Arizona NMHC select Arizona

*Note that considering Phoenix/Tucson AQCR totals for SO_X, NO_X, and NMHC would yield identical correlations because we have assumed that the AQCR emissions are a constant fraction of total Arizona emissions. If we wish to consider Phoenix/Tucson AQCR emissions, we need only make an adjustment in the regression coefficients according to the parameters given in Appendix C.

smelter SO_X as (by far) the most significant term for each of the six data sets. For five of the data sets, Arizona smelter SO_X is the only significant variable.* Table 7 summarizes the results of regressing extinction versus Arizona smelter SO_X. The consistency of the extinction/emission (regression) coefficients from site-to-site- and the high t-statistics at all sites are very encouraging. It is also encouraging that the extinction/emission coefficients are of approximately the same magnitude as (actually slightly higher than) the .01 to .03 $(10^4\ m)^{-1}/(1000\ TPD)$ values obtained in the copper strike analysis at sites on the order of 50 to 200 miles from smelters. The reader should note that the historical trend analysis is essentially independent of the 1967-1968 copper strike analysis. The 1967-1968 copper strike just partially affects 2 of the 28 yearly data points, and these two data points are not outliers in the regression (note that yearly emission levels for 1967 and 1968 were at or above the levels for the entire 1950's). We have redone the historical regression analyses eliminating the data for 1967-1968 and have obtained nearly identical correlation coefficients, regression coefficients, and t-statistics.

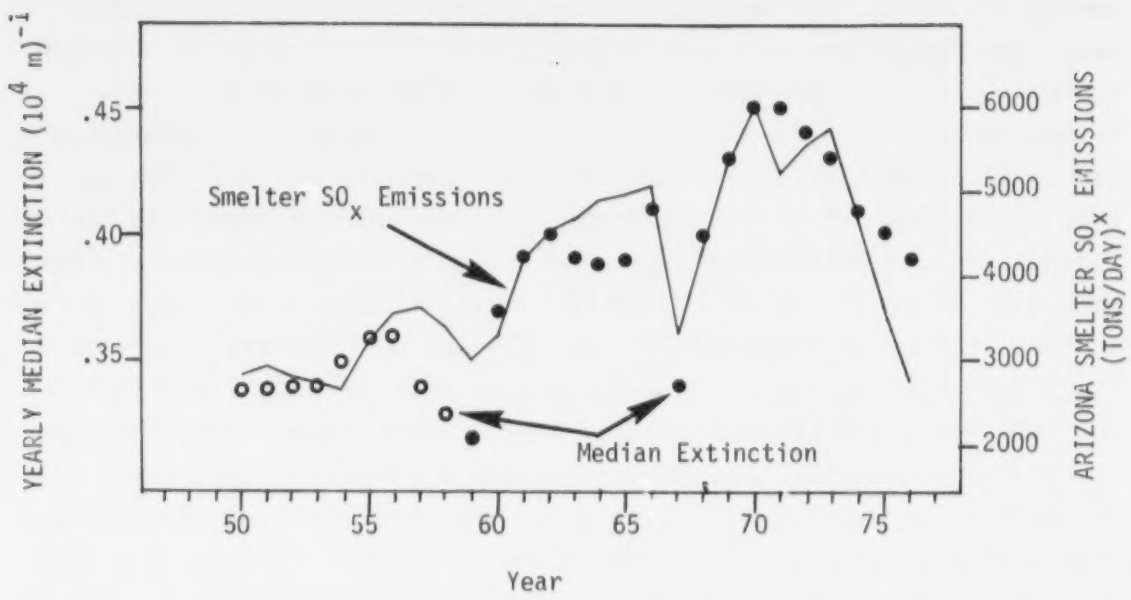
TABLE 7. REGRESSIONS OF HISTORICAL EXTINCTION LEVELS VERSUS HISTORICAL SMELTER SO_X EMISSION LEVELS

DATA SET	REGRESSION COEFFICIENT $(10^4\ m)^{-1}/(1000\ TPD)$	t-STATISTIC ($t \sim 1.7$ for 95% confidence)
Tucson (1950-1975)	.035	11.1
Tucson (1959-1975)	.038	7.2
Phoenix (1959-1975)	.041	5.4
Winslow (1948-1973)	.047	4.5
Prescott (1948-1975)	.031	5.0
Prescott (1948-1969)	.039	4.4

Figures 32 through 35 illustrate graphically the especially strong relationships between smelter emissions and visibility at Tucson and Phoenix.**

*The only exception is Tucson (1959-1975) where Arizona NMHC enters as a secondary variable.

**Note that the data point for 1976 is added to these figures. All of our regression analyses extended only to 1975 because we could obtain data on emissions for most sources only through 1975. Data for both visibility and smelter emissions were, however, available through 1976.



Note: o versus • denotes the "apparently not significant" site relocation in 1958 (see Chapter 3).

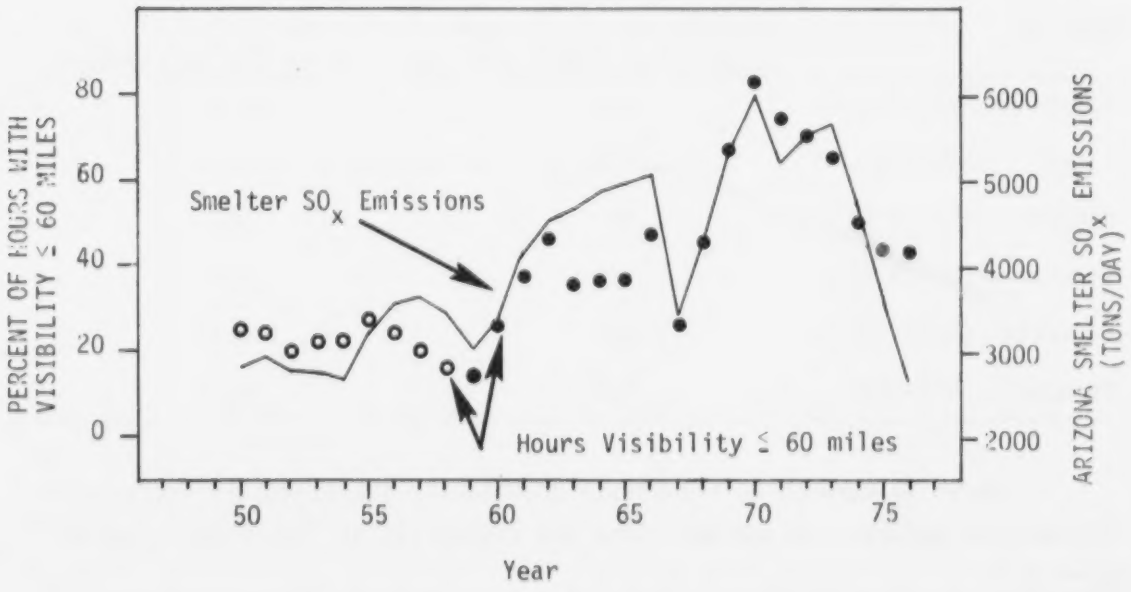
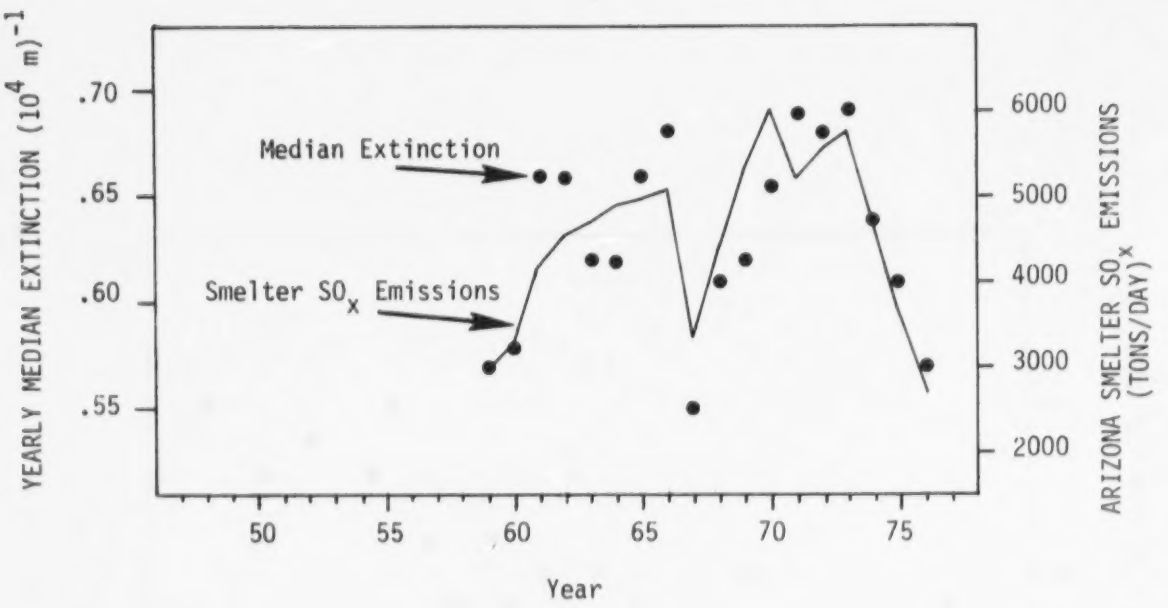


Figure 32. Tucson time series data on extinction and hours of restricted visibility versus historical smelter SO_x emissions for Arizona.



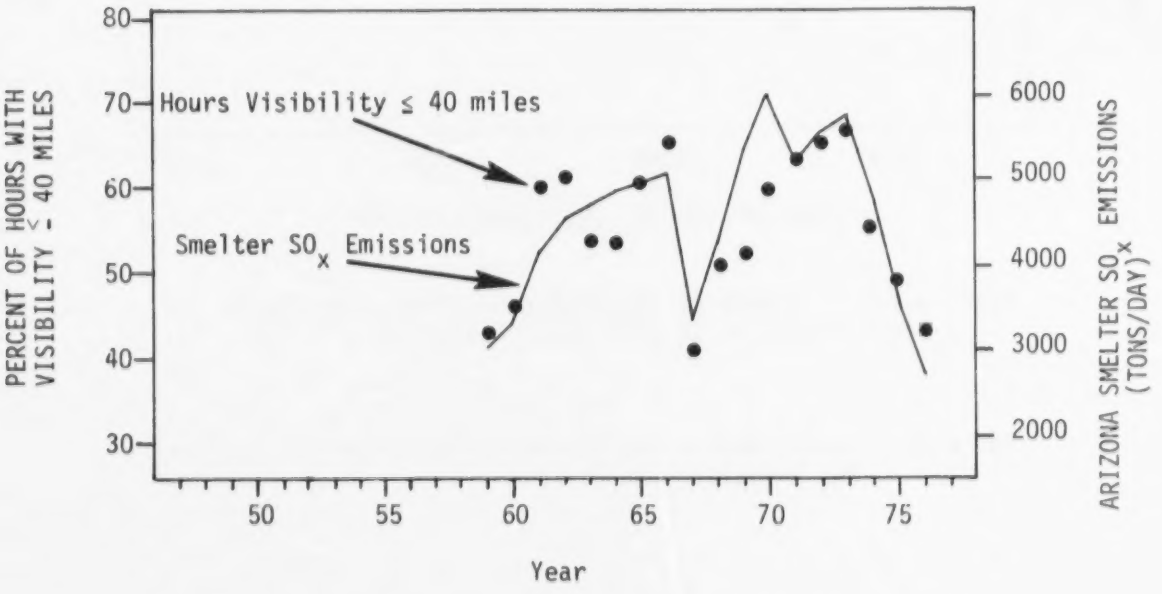
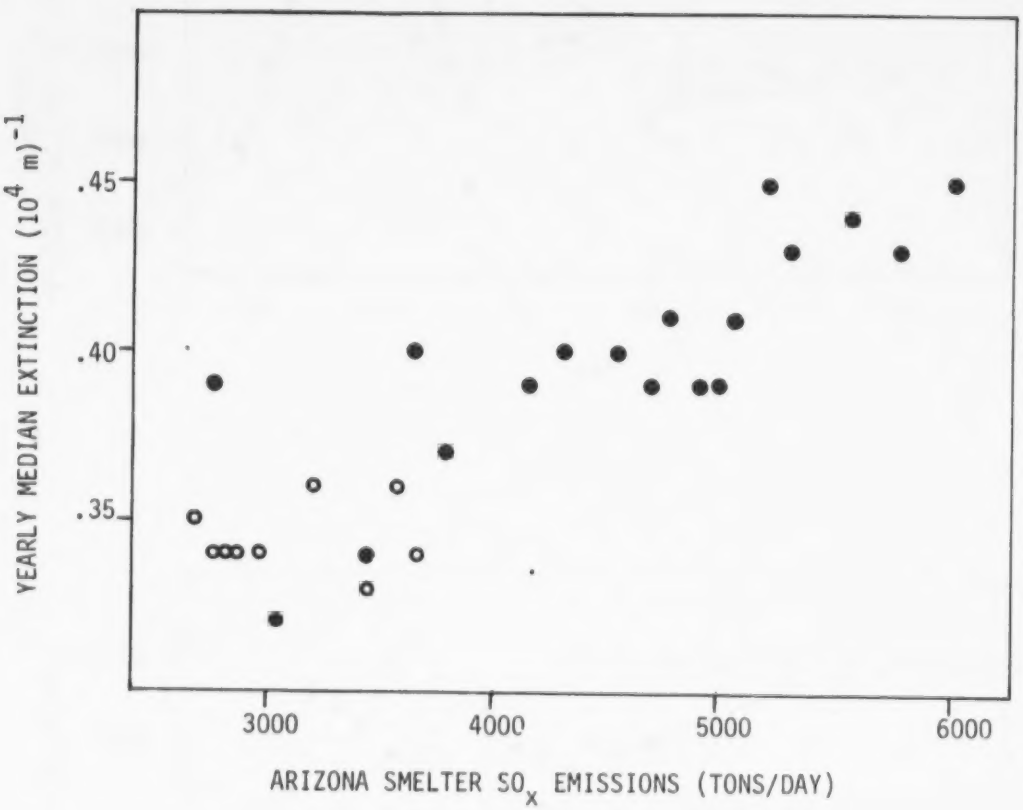


Figure 33. Phoenix time series data on extinction and hours of restricted visibility versus historical smelter SO_x emissions for Arizona.



Note: o versus • denotes the "apparently not significant" site relocation in 1959 (see Chapter 3).

Figure 34. Yearly median extinction at Tucson versus smelter SO_x emissions for Arizona.

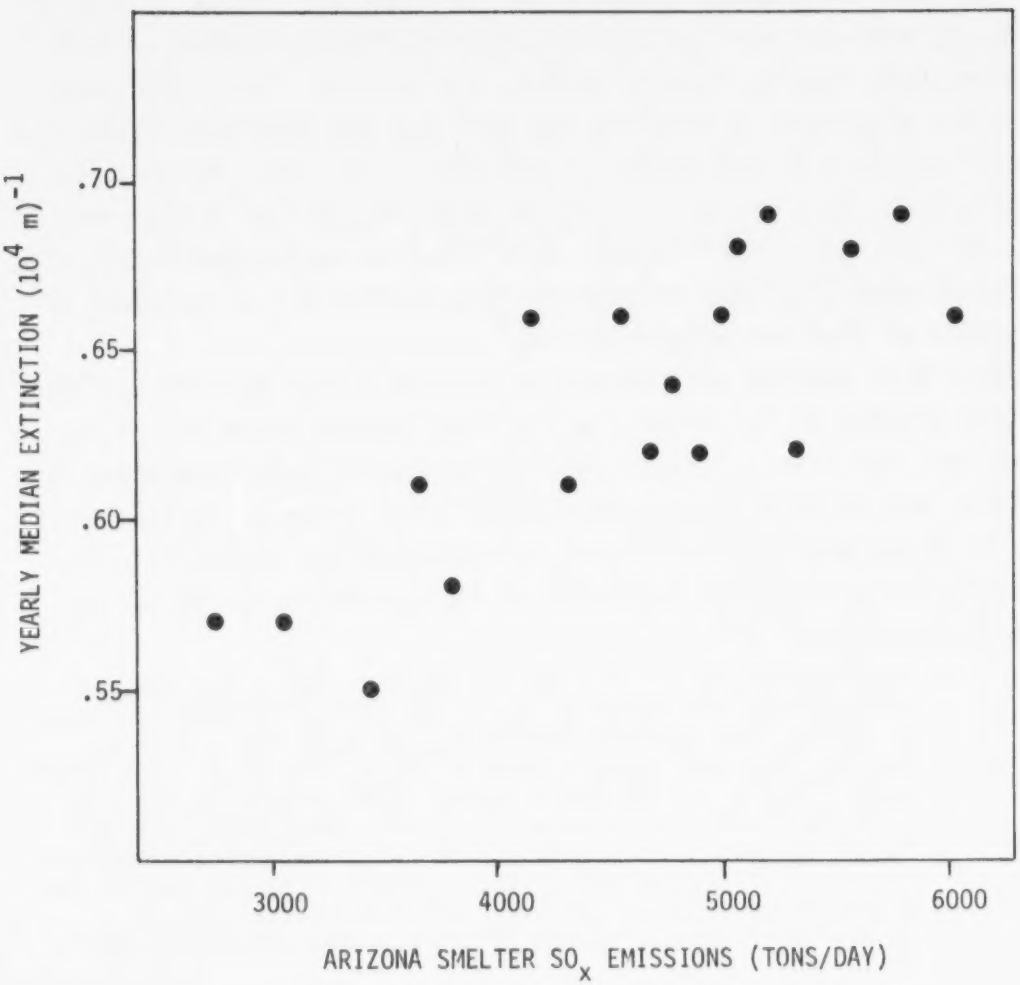


Figure 35. Yearly median extinction at Phoenix versus smelter SO_x emissions for Arizona.

Figures 32 and 33 present time series plots of yearly extinction versus smelter SO_x and of yearly hours with reduced visibility versus smelter SO_x. Figures 34 and 35 present scatter diagrams of yearly extinction versus smelter SO_x emissions.

The above trend analysis apparently indicates that changes in copper smelter SO_x emissions were the principal factor affecting historical visibility levels at Tucson, Phoenix, Winslow, and Prescott. This conclusion makes sense physically, considering that smelters have been the overwhelming source of secondary aerosol precursor emissions in Arizona. The analyses for the six data sets yield extinction/emission coefficients on the order of $.04 \pm .005$ $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$. This value for the extinction/emission coefficient appears relevant to regional haze at distances on the order of 50 to 200 miles from the emission source.*

Because of problems with respect to intercorrelated emission variables and limited number of data points, we could not isolate the effect of NO_x and NMHC emissions on extinction trends in Arizona. However, there are indications that, although these effects appear to be secondary to the impact of the large SO_x emissions in Arizona, they nevertheless are significant. Some evidence concerning the importance of NO_x and NMHC to visibility in Arizona is as follows:

- The emission/extinction coefficient for smelter SO_x that we derived from the trend analysis, $.04$ $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$, is higher than the emission/extinction coefficient that we derived from the copper strike analysis, $.01$ to $.03$ $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$. This could be explained in part by the fact that the copper strike essentially involved changes only in SO_x,** while the trend analysis involved concurrent long-term increases in NO_x and NMHC. The regression coefficients in the trend analysis may be slightly inflated because they also partly represent the effect of intercorrelated NO_x and NMHC emissions.
- Median visibility in central Phoenix is 40 miles, significantly lower than the 60 mile median visibility found in nonurban areas of southeastern Arizona. Some of this difference may

*The weighted average distances between the sites and the smelter SO_x emissions are as follows: Tucson - 80 miles, Phoenix - 120 miles, Winslow - 170 miles, and Prescott - 190 miles.

**Simple calculations convincingly indicate that reduced commuter travel by smelter workers during the strike would produce negligible changes in NO_x and NMHC emissions.

be due to greater suspended dust levels in the city. However, the difference may also be explained by the presence of urban photochemical smog (from NO_x and NMHC emissions) which contains nitrate and organic aerosols and also serves to increase the amount of SO_2 converted to sulfate.

- The absolute reductions of sulfate and extinction during the 1967-1968 copper strike tended to be greater in urban areas than in suburban and nonurban areas. This probably reflects the role of urban photochemical smog in enhancing the amount of SO_2 converted to sulfate.

REGRESSION ANALYSES FOR OTHER LOCATIONS

The regression studies for the other four sites (Salt Lake City, Denver, Grand Junction, and Ely) did not fare as well as the Arizona regressions. The analyses provided some hints that the impact of the Arizona smelters may extend well north of Arizona, and that growth in the photochemical precursors (NO_x and NMHC) was the key factor related to historical visibility changes in the urban areas of Salt Lake City and Denver. However, because of inconsistencies in the regression coefficients from site to site, and because the correlations (except for Salt Lake City) were rather low, we cannot place great faith in these conclusions. The lack of very large local emission changes (such as that which occurred among the Arizona smelters) and the problem of intercorrelated emission variables made it impossible to quantify, with confidence, extinction/emission coefficients based on the regressions for these four sites.

The following subsections describe the regression analyses for the four sites in the northern part of the study region. The sites are discussed in descending order with respect to the degree of correlation found in the regression studies.

Salt Lake City

The Salt Lake City regressions were conducted for the years 1955 to 1975. In the first set of regressions, the emission variables included total NO_x, total NMHC, and total SO_x for the Salt Lake City (Wasatch Front) AQCR.* In some cases the SO_x variable was divided into two variables:

*Identical correlations would be obtained using total Utah emissions, since we have assumed that the AQCR emission trends are constant multiples of respective trends for the entire state (see Appendix C).

Magna copper smelter SO_x and non-smelter SO_x.

The extinction trends for Salt Lake City correlated significantly with total NO_x (R = .87) and total NMHC (R = .78), but insignificantly with the various SO_x emission trend variables. A colinearity problem exists because (as shown in Table 5 for Utah) NO_x and NMHC trends are highly intercorrelated, and both are significantly correlated in a negative manner with SO_x. Essentially, the extinction trends at Salt Lake City from 1955 to 1975 followed the upward trends in NO_x and NMHC rather than the downward or constant trends in SO_x.

The multiple regressions indicate significant regression coefficients for both NO_x (t-statistic = 4.5) and NMHC (t = 2.3). Compared to our previous results, the extinction/emission (regression) coefficients are quite high: 1.26 $(10^4 \text{ m})^{-1}$/(1000 TPD) for NO_x and 1.39 $(10^4 \text{ m})^{-1}$/(1000 TPD) for NMHC. The rather large magnitude of these coefficients might partly be explained by the localized (air basin) scale of the analysis. In Chapter 4 we noted that the extinction/emission coefficients for SO_x seemed to become much greater when the distance from the source was reduced to less than 50 miles.

The importance of the photochemical pollutants (NO_x and NMHC) to extinction in Salt Lake City is not inconsistent with our previous findings for that area. For example, we have noted previously that extra extinction (extinction above-and-beyond blue-sky scatter) dropped only 8% at Salt Lake City with the SO_x reduction of the 1967-1968 copper strike (Trijonis and Yuan, 1978a). Also, an extinction budget for Salt Lake City (Trijonis and Yuan, 1978a) indicates that sulfates account for only one-third of extra extinction in that area. Even the fraction of extinction attributable to sulfates may depend on photochemical precursor emissions as well as SO_x emissions because of the potential role of photochemical smog in oxidizing SO_2 to sulfate.

A second set of regressions was run for Salt Lake City including Arizona smelter SO_x emissions as well as the local emission variables. Arizona smelter emissions correlated significantly with Salt Lake City extinction (R = .79) and entered the regression equation as a secondary but significant variable (t = 3.6) with a regression coefficient of .03 $(10^4 \text{ m})^{-1}$/(1000 TPD). Based on this result, one might speculate that the Arizona

smelter emissions have a significant effect as far as Salt Lake City. However, because of colinearity problems (Arizona smelter SO_x trends happen to correlate well with Salt Lake City NO_x and NMHC trends) and because of the extremely questionable physical basis for the conclusion (e.g. the long transport distances over terrain of increasing elevation), we would place very little confidence in that speculation.

Denver

Because of a "possibly significant" site relocation in 1969 (see Chapter 3), the Denver regression study was performed for two time periods: 1948 to 1968 and 1948 to 1975. The independent variables used in the regressions were total NO_x, total NMHC, and total SO_x emission trends for the Denver AQCR. For both time periods, extinction correlated at a marginal significance with NMHC emissions (R = .39 and .50) and NO_x emissions (R = .39 and .41) but insignificantly with SO_x emissions.

The stepwise multiple regressions selected NMHC emissions as the only significant variable with regression coefficients of 0.27 and 0.29 $(10^4 \text{ m})^{-1}$/(1000 TPD) and t-statistics of 1.9 and 2.9 respectively for the two time periods. There is a major colinearity problem, however, between NMHC and NO_x emissions which correlated with each other at a level of 0.87 (see Table 5). Excluding NMHC from the regressions left NO_x as the only significant variable with regression coefficients of 0.40 and 0.23 $(10^4 \text{ m})^{-1}$/(1000 TPD) and t-statistics of 1.8 and 2.3. The regression (extinction/emission) coefficients are much higher than those found for SO_x in the Arizona study; again this could reflect the more localized nature (air basin scale) of the effects being considered.

The Denver results are consistent with the Salt Lake City results in implicating NO_x and NMHC as the most significant local emission variables related to historical extinction trends. We cannot be very certain, however, about the Denver results because the statistical significance of the correlation and regression coefficients is only marginal.

In another set of regressions, we added Arizona smelter SO_x to the list of emission variables for Denver. Arizona smelter SO_x correlated with Denver extinction at levels of .60 and .61 for the two time periods, respectively, and became the only variable retained in the multiple stepwise regressions with regression coefficients of .027 and .021 $(10^4 \text{ m})^{-1}$/(1000 TPD) and t-statistics of 3.2 and 3.9. This seems to imply that Arizona smelter

SO_x emissions may affect visibility at Denver. However, because of the colinearity problems (Arizona smelter SO_x trends correlate highly with Denver NO_x and NMHC trends) and the questionable physical basis of linking Arizona smelter SO_x with Denver visibility, we cannot attach confidence to this conclusion.

Grand Junction

Because of the "apparently not significant" site relocation in 1950, the Grand Junction analysis was performed for two time periods: 1951-1975 and 1948-1975. The emission variables chosen for the analysis were Colorado plus Utah totals for SO_x, NO_x, and NMHC as well as Arizona smelter SO_x emissions.

The multiple stepwise regression based on 1951-1975 data selected Arizona smelter SO_x as the only significant variable with a marginal correlation coefficient of 0.39. The regression coefficient, .005 $(10^4 \text{ m})^{-1}$/(1000 TPD), was marginally significant ($t = 2.0$) but seemed consistent with the values obtained for Arizona sites $\sim$ .04 $(10^4 \text{ m})^{-1}$/(1000 TPD) considering the much greater distance to the smelters.

The regressions based on 1948-1975 data indicated that none of the emission variables were significant at the 95% confidence level. Two of the variables, Colorado and Utah total SO_x and Arizona smelter SO_x, were almost significant at the 95% confidence level. The regression coefficients, .02 $(10^4 \text{ m})^{-1}$/(1000 TPD) for Colorado plus Utah SO_x and .004 $(10^4 \text{ m})^{-1}$/(1000 TPD) for Arizona smelter SO_x, are fairly consistent with the results of the copper strike analysis, considering the transport distances involved. These results should be viewed as very tenuous, however, because of the lack of statistical significance and the ever-present colinearity problem.

Ely

The Ely regressions were conducted for two periods: 1962-1975 and 1955-1975 (a "possibly significant" site relocation occurred in 1961). The emission variables used included total SO_x, smelter SO_x, non-smelter SO_x, total NO_x, and total NMHC for Nevada as well as Arizona smelter SO_x.

The extinction trends for 1962-1975 did not correlate significantly with any of the emission variables, but the extinction trends for 1955-1975 correlated marginally with all the variables. Multiple stepwise

regression with the 1955-1975 data selected Nevada NMHC as the only significant variable, but the regression coefficient, 9.3 $(10^4\ m)^{-1}/(1000\ TPD)$, was far out of line with the values obtained in our other analyses. The analysis did not make much sense at Ely, especially considering the proximity of that site to the McGill smelter and our earlier finding that Ely showed a significant improvement in visibility during the 1967-1968 copper strike.

We are not sure why the regression analysis fared so poorly at Ely, but one reason might be the fact that we used a very high (90th) percentile extinction at Ely in order to avoid extrapolation of the visibility frequency distribution. The 90th percentile extinctions (lowest visibilities) might be predominantly affected by yearly weather fluctuations (e.g. precipitation days) which could mask the effect of emission changes.

CHAPTER 6

CONCLUSIONS AND ILLUSTRATIVE APPLICATIONS

This chapter summarizes our conclusions concerning extinction/emission coefficients for the Southwest and demonstrates how such coefficients can be applied. It must be emphasized that the applications presented here should be regarded only as illustrative because high uncertainty exists in the extinction/emission coefficients which serve as the bases for these applications. Further work needs to be done both with empirical analyses and large-scale modeling calculations before we can be more certain about the relationship between aerosol precursor emissions and regional haze in the Southwest.

EXTINCTION/EMISSION COEFFICIENTS FOR THE SOUTHWEST

This section lists the conclusions we have reached with respect to regional extinction/emission coefficients for the Southwest. The discussion is organized according to three spatial scales: mesoscale ($\sim$ 50 to 200 miles from the source), air basin scale ($\lesssim$ 50 miles from the source), and synoptic scale ($\sim$ 200 to 500 miles from the source).

Mesoscale ($\sim$ 50 to 200 miles)

Airport visibility data and NASN sulfate data during the 1967-1968 copper strike both indicate that the regional extinction/emission coefficient for SO_x emissions is approximately .01 to .03 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$ on a scale of 50 to 200 miles from the source, For the same spatial scale, the historical trend regressions with 6 Arizona data sets imply an extinction/emission coefficient of $.04 \pm .005$ $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$. The coefficient derived from the Arizona regression analysis, however, may be somewhat inflated because of colinearity problems (i.e. historical increases in NO_x and NMHC occurred concurrently with the increasing trend in SO_x). Considering all our analyses, a regional extinction/emission coefficient of .01 to .03 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$ seems most reasonable for the mesoscale.* Unfortunately, we could not derive estimates of extinction/emission coefficients pertinent to mesoscale effects of NO_x and NMHC.

*Note that all of our estimates of extinction/emission coefficients for gaseous precursors may be somewhat inflated (possibly on the order of 10-30% or more) by the omission of primary particulates from the analysis.

Air Basin Scale ($\lesssim$ 50 miles)

There is a very high degree of uncertainty in our estimates of extinction/emission coefficients for the air basin scale ($\lesssim$ 50 miles from the source) in the Southwest. The 1967-1968 copper strike analysis indicated that SO_x emissions might produce extinction on the order of .1 to .4 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$ within 10 to 15 miles from a source, but this conclusion was made tenuous by several complicating factors in the analyses (see Chapter 4, page 52). The regression studies for Salt Lake City and Denver implicated photochemical precursor (NO_x and NMHC) emissions as being most closely tied to historical visibility trends in those urban areas and implied that the extinction/emission coefficients might be on the order of .2 to 1.4 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$ for both NO_x and NMHC on an air basin scale. This conclusion, however, was uncertain because of statistical colinearity problems in the regression analysis.

Synoptic Scale ($\sim$ 200 to 500 miles)

Our results concerning the effect of aerosol precursor emissions at distances greater than 200 miles from the source are likewise very uncertain. Sulfate data during the copper strike imply an extinction/emission coefficient on the order of .01 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$ at distances 250 to 375 miles from the copper smelters, but visibility data at two airports fail to confirm significant effects at these distances during the strike. The historical regression analyses for Grand Junction, Denver, and Salt Lake City indicate statistically significant extinction/emission coefficients of .005 to .03 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$ at distances of 400 to 500 miles from the smelters, but this result is clouded by problems of colinearity in the regressions. It may be that an extinction/emission coefficient on the order of .01 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD})$ is appropriate for synoptic scale SO_x effects in the Southwest, but this conclusion should be confirmed by analyzing several more airports during the 1967-1968 copper strike before we can lend it any credence.*

*The visibility analyses reported here are based only on airport data available in computerized form. Hard-copy visibility data may be available for several other airports in northern Arizona and southern Utah/Colorado.

ILLUSTRATIVE APPLICATIONS

This section presents two examples which illustrate how extinction/emission coefficients might be used to conduct order of magnitude calculations concerning regional haze in the Southwest. In the second example we obtain a gross check on our results by comparing our predictions to existing geographical patterns of nonurban visibility in the Southwest.

Mesoscale Haze from a Large Source of SO_x

As a simple hypothetical example, we consider the following: Assuming a background visibility of 75 miles, what would be the effect of a 500 TPD SO_x source on regional haze at distances of 50 to 200 miles from the source?

From the Koschmeider relationship,* the 75 mile background visibility translates to an extinction of 0.324 $(10^4 \text{ m})^{-1}$. Assuming an extinction/emission coefficient of .02 ± .01 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$, the 500 TPD SO_x would increase mesoscale extinction by .01 ± .005 $(10^4 \text{ m})^{-1}$. Adding this to the background extinction and substituting back into the Koschmeider relationship, we conclude the mesoscale effect would be to reduce visibility from 75 miles to 72.8 ± 1.1 miles.

Existing Patterns in Nonurban Visibility

A companion report on existing visibility levels in the United States (Trijonis and Shapland, 1978) uses airport, nephelometry, and photographic photometry data for 1974-1976 to characterize the geographical pattern of nonurban visibility in the Southwest. It is found that median nonurban visibility is on the order of 78 miles in Utah, Colorado, and Nevada but falls to around 60 miles in central and southern Arizona. Can this pattern be accounted for by the mesoscale effects of the copper smelter emissions in Arizona?

Noting that the Arizona smelters averaged 3720 TPD for the period 1974-1976, and assuming a mesoscale extinction/emission coefficient of .02 $(10^4 \text{ m})^{-1}/(1000 \text{ TPD } SO_x)$, calculations parallel to those in the last example indicate that the Arizona smelters would reduce a background visibility of 78 miles down to 63 miles. The agreement with the observed nonurban visibility in southern/central Arizona (60 miles) is an encouraging sign that

*See Equation (1), page 42.

we may have the right order of magnitude for the mesoscale SO_x extinction/ emission coefficient.

REFERENCES

AQMP (Air Quality Maintenance Plan), Preliminary Emissions Inventory and Air Quality Forecast 1974-1995, Final Report of the Boundary and Forecasting Committee of the Air Quality Maintenance Planning Policy Task Force for Southern California, April 1976.

Cass, G.R., "The Relationship Between Sulfate Air Quality and Visibility at Los Angeles," Caltech Environmental Quality Laboratory, Memorandum #18, August 1976.

EPA (Environmental Protection Agency), "Monitoring and Air Quality Trends Report, 1974," EPA-450/1-76-001, February 1976.

Latimer, D.A., et al., "The Development of Mathematical Models for the Prediction of Anthropogenic Visibility Impairment," Draft Final Report, Prepared at Systems Applications, Inc., San Rafael, California, Under Contract #68-01-3947, for Environmental Protection Agency, 1978.

Macias, E.S., et al., "Characterization of Visibility Reducing Aerosols in the Southwestern United States: Interim Report on Project VISTTA", Prepared by Meteorology Research Inc. under EPA Contract No. 68-02-2713, January 1979.

Niemann, B., Regional modeling studies in progress under contract to EPA Office of Research and Development, Teknekron, Berkley, California, 1978.

NOAA (National Oceanic and Atmospheric Administration), Climatic Atlas of the United States, National Climatic Center, Asheville, N.C., 1977.

Trijonis, J. and K. Yuan, "Visibility in the Southwest: An Exploration of the Historical Data Base," EPA-600/3-78-039, April 1978 (a).

Trijonis, J. and K. Yuan, "Visibility in the Northeast: Long-Term Visibility Trends and Visibility/Pollutant Relationships," EPA-600/3-78-075, 1978 (b).

Trijonis, J. and D. Shapland, "Existing Visibility Levels in the U.S.-Isopleth Maps of Visibility in Suburban/Nonurban Areas During 1974-1976," Prepared at Technology Service Corporation, Santa Fe, N.M., Under Grant #802815 for EPA Office of Air Quality Planning and Standards and EPA Environmental Science Research Laboratory, 1978.

Ursenbach, W.O., et al., "Visibility Models for the Arid and Semi-Arid Western United States," Paper # 78-43.6, Presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, 1978.

Waggoner, A.P., et al., "Sulfate-Light Scattering Ratio as an Index of the Role of Sulphur in Tropospheric Optics," Nature, Vol. 261, No. 5556, pp. 120-122, 1976

White, W.H. and P.T. Roberts, "On the Nature and Origins of Visibility-Reducing Aerosols in the Los Angeles Air Basin," Atmospheric Environment, Vol. 11, p. 803, 1977.

APPENDIX A

EXPLANATION OF EMISSION TREND ESTIMATES

This appendix describes how 1948 to 1975 emission trends were calculated for sulfur oxides (SO_x), nitrogen oxides (NO_x), and non-methane hydrocarbons (NMHC) for the states: Arizona, Colorado, Nevada and Utah. It also includes tables listing detailed trend estimates for each source type considered.

Introduction

NEDS, the 1973 National Emissions Report (EPA, 1976), provides emission inventories which indicate that in each of the states considered, 80-100% of the SO_x, 90-100% of the NO_x, and 70-90% of the HC emissions are produced by a relatively few source types: copper smelters, steam-electric power plants, gasoline vehicles, diesel vehicles, railroads, petroleum industries , industrial boilers, commercial/residential sources, gasoline evaporation, and solvent evaporation. A good estimate of the historical trends in emissions can be made by considering the contributions from just these sources.

Discussions in AP-42, Compilation of Air Pollution Emissions Factors (EPA, 1977), supplied methods and insights to determine emission factors for most of these source types. When a method for estimating emission factors for a specific source type was not readily available, we often resorted to computing an emission factor so that our 1973 emission estimate is consistent with the corresponding datum reported in NEDS.

A major contribution to our historical data base was made by FEDS, Federal Energy Data System: A Statistical Summary (DOE, 1978), the Depart- of Energy's compilation of fuel use data by consumer type, state, and year, back to 1960. Other valuable supplies of data come from the Minerals Yearbooks (BOM, 1948-1975), annual publications of the Department of Interior's Bureau of Mines, which report in considerable detail the production activities and sales of the minerals/fuels industries. Highway

Statistics: A Summary to 1975 (DOT, 1975) provides detailed data on gasoline and diesel fuel consumption, essential to several of our calculations. Additional data were supplied by many other sources; these are mentioned in the discussions that follow.

There are many more sources of data which we collected, considered, and discarded for one reason or another. Usually these sources either were discarded because they were less complete than some other data source or they were discarded in favor of data which seemed to be a more direct indication of the activity under consideration.

Copper Smelters

Historically, copper smelters have produced the preponderance of SO_x emitted in the Southwest. The smelters of relevance to this trend study include seven in Arizona, one in Nevada, and one in Utah.*

For 1972 and later years, detailed SO_x emission data for Arizona copper smelters are presented in the First Annual Report on Arizona Copper Smelter Pollution Control Technology (Larson and Billings, 1977). Yearly emissions prior to 1972 are determined by factoring according to Arizona copper production as listed in the Minerals Yearbooks. The production related emission factor is adjusted in 1966, 1969, and 1971 to account for the partial SO_x controls installed at Phelps Dodge/Morenci, Kennecott/Hayden, and Asarco/Hayden during those years** (Weisenberg et al., 1976).

SO_x emissions at the Kennecott/McGill, NV smelter were approximately 700 tons/day in 1973 (EPA, 1976; Weisenberg et al., 1976). Emission trends for all other years are assumed proportional to copper production in Nevada, as reported in the Minerals Yearbooks, because no controls were installed on the McGill smelter.

SO_x emissions at the Kennecott/Salt Lake City smelter are determined from data on average daily emissions and number of yearly operating days

---

*There are also two copper smelters operating in New Mexico, but New Mexico emission trends are not included in this report.

**The overall percent sulfur removed in Arizona smelters has changed historically as follows: 3% in 1965, 6% in 1966, 9% in 1969, 13% in 1971, 16% in 1972, 21% in 1974, 37% in 1975, and 50% in 1976.

supplied for each year (1948-1975) by Kennecott Copper (Heaney, 1978).

Table A-1 summarizes the copper smelter SO_x emission trends for the three states.

TABLE A-1. TRENDS IN SO_x EMISSIONS FROM COPPER SMELTERS

SO_x (TONS/DAY)

YEAR	Arizona	Nevada	Utah
48	2650	340	990
49	2540	280	970
50	2850	390	1300
51	2940	420	1180
52	2800	430	1160
53	2790	460	1110
54	2670	520	860
55	3210	590	770
56	3570	600	900
57	3650	580	500
58	3440	490	400
59	3040	420	270
60	3810	570	460
61	4150	580	580
62	4550	620	680
63	4670	610	520
64	4890	500	500
65	4970	530	600
66	5070	590	600
67	3440	380	290
68	4310	570	420
69	5320	780	640
70	6030	800	520
71	5200	720	350
72	5570	750	410
73	5780	700	560
74	4770	630	510
75	3640	600	440

Power Plants

Sulfur contents and emission factors for power plants were derived from the fuel consumption and emission data reported in Steam-Electric Plant Air and Water Control Data (DOE, 1969-73). Statewide factors as well as factors for individual plants were computed for the years 1969, 1970, and 1971. The average sulfur contents and emission factors for these three years were assumed to apply throughout the 28 years under study.

The "Air and Water Control Data" only cover 5 years, so emission trends were estimated using the fuel usage data listed in Steam-Electric Plant Construction Cost and Annual Production Expenses (FPC, 1948-74). These data were adjusted slightly so that they are consistent with the "Air and Water Control Data" in the years where both are available. Neither data source covers 1975, so the change in fuel usage reported in FEDS for that year was used to estimate the pollutants emitted in each state.

Table A-2 lists the estimated NO_x and SO_x emitted by power plants in each state during the years, 1948-1975. Table A-3 presents the same information for some of the larger power plants in the area under study.

Gasoline Vehicles

In order to estimate the NO_x and NMHC emitted by gasoline powered vehicles, it was necessary to construct an average vehicle emission factor for each year, each pollutant, and for low and high altitudes. This was done using the method suggested in AP-42. The data used included the yearly number of vehicles in operation by model year (MVMA, 1976, 1977), the average miles traveled per year by vehicle age (EPA, 1977), and the AP-42 emission factors corrected to an average speed of 40 miles per hour. These considerations produced a high and low altitude, fleet-averaged emission factor for each pollutant and for each year for both light duty vehicles and heavy duty vehicles.

The emission factors relating to vehicle miles of light duty travel and vehicle miles of heavy duty travel were combined with vehicle use data (i.e. percent of total vehicle miles traveled by cars and trucks, and the average miles per gallon for cars and trucks (DOT, 1967 and 1974; MVMA, 1977)

TABLE A-2. TRENDS IN SO_x AND NO_x EMISSIONS FROM STEAM-ELECTRIC POWER PLANTS

YEAR	Arizona (tons/day)		Colorado (tons/day)		Nevada (tons/day)		Utah (tons/day)	
	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x
48	0	4	10	12	0	0	2	2
49	0	4	4	8	0	0	2	2
50	0	5	5	9	0	0	2	2
51	0	6	8	14	0	0	3	2
52	0	5	7	14	0	0	8	7
53	0	8	9	21	0	0	15	13
54	0	11	9	21	0	0	13	16
55	0	15	12	25	0	0	18	23
56	0	21	15	27	0	3	18	24
57	0	20	11	27	0	4	25	28
58	0	20	13	31	0	4	27	25
59	0	23	14	36	0	5	20	26
60	0	31	29	44	0	6	32	27
61	0	37	32	43	0	9	32	28
62	19	49	36	45	0	10	24	23
63	14	42	44	51	0	9	22	21
64	11	39	48	57	0	12	23	21
65	6	25	30	58	5	18	22	21
66	7	31	75	80	8	24	23	25
67	7	31	83	88	9	24	22	23
68	8	34	84	93	14	29	23	22
69	7	40	84	93	17	36	23	21
70	1	41	97	102	15	39	25	22
71	2	46	98	103	33	68	26	21
72	6	51	99	115	78	117	25	23
73	45	71	141	147	85	124	29	27
74	97	101	138	148	99	129	34	31
75	157	136	168	165	103	128	58	51

TABLE A-3. TRENDS IN SO_x AND NO_x EMISSIONS FROM INDIVIDUAL POWER PLANTS

YEAR	Arapahoe (CO) (tons/day)		Cherokee (CO) (tons/day)		Four Corners (NM) (tons/day)		Mohave (NV) (tons/day)		San Juan (NM) (tons/day)		Navajo (AZ) (tons/day)		Huntington (UT) (tons/day)	
	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x
48														
49														
50														
51	1.8	3.9												
52	3.2	5.6												
53	2.9	6.2												
54	1.7	5.2	0.1	0.2										
55	2.7	6.3	0.1	0.3										
56	5.3	9.1	0.0	0.0										
57	2.6	7.7	0.6	1.3										
58	3.6	7.5	2.3	5.3										
59	6.9	8.9	8.9	11										
60	7.6	9.8	11	14										
61	9.0	10.6	13	16										
62	7.4	8.9	20	18										
63	9.9	10.3	25	25	29	20								
64	5.4	6.9	24	24	67	45								
65	5.5	6.6	22	23	87	59								
66	6.4	7.8	24	25	73	50								
67	6.9	8.7	29	27	88	60								
68	5.8	8.3	31	30	85	58								
69	6.8	7.3	34	39	101	69								
70	8.2	9.0	42	44	198	135								
71	9.5	11	42	47	241	165	13	18						
72	11	12	45	49	250	171	50	61						
73	16	16	58	57	268	183	56	66	4.2	2.4				
74	13	14	43	46	251	172	65	76	42	24	49	35	12	10
75	19	18	61	59	210	143	66	77	55	31	113	82	32	26

to provide one fuel-use related factor for each year and for low and high altitudes. These were then used in conjunction with the highway gasoline data (DOT, 1975) to produce yearly estimates of emissions from 1948 to 1975. Of the four states under study, only Colorado was taken to be high altitude.

The hydrocarbon emissions from gasoline powered vehicles are 98.5% non-methane (Trijonis and Arledge, 1976). This factor was introduced to produce the final NMHC estimates reported in Table A-4.

Diesel-Powered Vehicles

Trends in fuel use by diesel powered vehicles were estimated from "Private and Commercial Highway Use of Special Fuels, By States, 1949-1975" appearing in Highway Statistics: Summary to 1975 (DOT, 1975). These data are not available before 1949, so the 1948 datum for each state was estimated by factoring according to total fuel used (DOT, 1975).

In order to use the emission factors recommended in AP-42, the fuel use data were converted into vehicle miles traveled using yearly average-miles-per-gallon figures for trucks (DOT, 1967; DOT, 1974; MVMA, 1977).

These calculations produced the NO_x emission trends listed in Table A-5.

Railroads

The Association of American Railroads (AAR, 1957; 1967; 1977) provides, in its yearly Statistics of Railroads of Class I in the United States, data on the various fuels used by Class I railroads. The data were multiplied by 1.05 to make them more representative of railroads of all classes (AAR, 1957; 1967; 1977).

At the present time, locomotives operate on diesel fuel and AP-42 gives emission factors for them only. The fuels of the past (coal and fuel oil) were assumed to have been burned in small, hand-fired, external combustion engines, and AP-42 emission factors appropriate for such engines were used.

Perry and Decarlo (1967) report a 2% average sulfur content for coal produced in the United States in 1964. This was the figure assumed in our calculations. Distillate fuel oil usually contains less than 0.3% sulfur (EPA, 1977); 0.3% was used here.

TABLE A-4. TRENDS IN NO_x AND NMHC EMISSIONS FROM GASOLINE-POWERED MOTOR VEHICLES

	Arizona (tons/day)		Colorado (tons/day)		Nevada (tons/day)		Utah (tons/day)	
YEAR	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x
48	36	113	41	237	11	35	30	96
49	36	112	44	253	11	36	32	101
50	40	122	47	276	13	39	35	107
51	44	142	52	300	14	45	36	115
52	50	159	55	317	16	49	36	115
53	53	170	57	332	18	56	38	120
54	53	168	59	341	18	57	39	122
55	59	187	62	360	20	63	41	131
56	63	198	64	369	20	64	45	142
57	68	213	67	386	21	66	47	148
58	73	228	69	396	22	69	49	153
59	78	247	74	424	24	75	50	158
60	85	268	76	438	25	79	52	165
61	89	280	80	439	27	85	55	172
62	95	298	83	479	32	99	57	181
63	102	310	90	510	36	112	61	191
64	107	325	93	522	38	116	64	193
65	110	328	97	535	41	121	64	194
66	115	330	100	543	42	119	65	198
67	117	329	103	545	42	119	69	198
68	127	345	116	573	45	123	70	205
69	151	374	128	582	50	123	75	212
70	172	375	151	595	59	127	86	213
71	195	374	173	596	65	125	98	210
72	230	388	201	619	76	129	109	213
73	255	383	221	582	83	124	126	200
74	244	341	229	535	82	115	133	186
75	261	336	248	535	91	117	133	182

TABLE A-5. TRENDS IN NO_x EMISSIONS FROM DIESEL POWERED VEHICLES

	NO_x (tons/day)			
YEAR	Arizona	Colorado	Nevada	Utah
48	5	3	3	3
49	5	3	3	4
50	7	5	4	4
51	9	6	5	5
52	10	8	6	7
53	12	9	7	7
54	13	11	8	8
55	14	13	8	9
56	16	14	8	11
57	18	16	9	12
58	20	17	9	13
59	21	18	9	13
60	23	19	9	14
61	23	19	10	14
62	25	21	11	15
63	29	24	13	16
64	31	25	14	18
65	32	25	14	18
66	35	27	14	19
67	38	29	14	20
68	42	32	17	23
69	49	34	18	24
70	50	36	20	26
71	60	41	21	26
72	67	47	23	32
73	79	56	26	38
74	80	56	29	39
75	84	56	29	40

These considerations provided an estimate of emissions produced annually on all railroads in the United States. In order to obtain an estimate of emissions for each state, the nationwide totals were factored so that the 1973 results are consistent with the railroad emissions reported in NEDS. Table A-6 contains the resulting figures.

Petroleum Industry

In Colorado and Utah, petroleum industry emissions are nonnegligible. The Minerals Yearbooks' report of yearly petroleum production by state was used to produce estimates of emission trends. This was done by using the petroleum industry emissions reported in NEDS as a base and causing them to vary yearly as petroleum production.

The results are listed in Table A-7.

Industrial Sources

Combustion of coal, natural gas, fuel oils, gasoline, and diesel fuel from industrial sources produces significant NO_x and SO_x. Emissions from the use of each fuel were estimated using the methods described in AP-42.

In order to arrive at final emission factors, several assumptions were made. Industrial coal was assumed to be 0.5% sulfur, while residual and distillate fuel oils were taken to be 1% and 0.2% respectively. These choices of sulfur contents produce emission estimates which are consistent with those listed in NEDS for the year 1973.

Distillate and residual fuel data are from FEDS after 1959. Before that, they are from "Mineral Industry Surveys" (BOM, 1949, 1951, 1953, 1957-62). The lists of industrial and oil company fuels were used because these data are most consistent with FEDS data in the years they overlap. In addition, the data were slightly adjusted to make them more comparable with the FEDS data and to insure consistency in trend estimates.

The gasoline and diesel figures were computed from data given in FEDS from 1960 to 1975. Before 1960, the data used are those given in Highway Statistics: Summary to 1965 (DOT, 1967) as "Nonhighway Use of Motor Fuel". These were factored so they match the FEDS data reasonably well in the years

TABLE A-6. TRENDS IN SO_x AND NO_x EMISSIONS FROM RAILROADS.

	Arizona (tons/day)		Colorado (tons/day)		Nevada (tons/day)		Utah (tons/day)	
YEAR	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x	NO_x
48	119	13	139	15	60	6	139	15
49	90	13	105	15	45	7	105	15
50	76	15	89	18	38	8	89	18
51	67	18	78	21	34	9	78	21
52	47	19	55	23	23	10	55	23
53	34	21	40	24	17	10	40	24
54	20	21	24	24	10	10	24	24
55	19	22	22	26	9	11	22	26
56	15	23	17	27	7	12	17	27
57	10	22	12	26	5	11	12	26
58	5	21	6	25	2	11	6	25
59	4	23	5	26	2	11	5	26
60	4	23	4	26	2	11	4	26
61	4	22	4	26	2	11	4	26
62	4	23	4	27	2	11	4	27
63	4	23	4	27	2	12	4	27
64	4	24	4	28	2	12	4	28
65	4	24	4	29	2	12	4	29
66	4	26	5	30	2	13	5	30
67	4	25	5	29	2	13	5	29
68	4	25	5	30	2	13	5	30
69	4	25	5	29	2	13	5	29
70	4	24	4	28	2	12	4	28
71	4	24	4	29	2	12	4	29
72	4	26	4	30	2	13	4	30
73	4	27	5	31	2	13	5	31
74	4	26	5	31	2	13	5	31
75	4	24	4	28	2	12	4	28

TABLE A-7. TRENDS IN NO_x AND SO_x EMISSIONS FROM PETROLEUM INDUSTRIES

	Colorado (tons/day)		Utah (tons/day)	
YEAR	SO_x	NO_x	SO_x	NO_x
48	3	1	0	0
49	4	2	0	0
50	4	2	0	0
51	4	2	1	0
52	5	2	1	0
53	6	2	1	0
54	7	3	1	0
55	8	3	1	0
56	9	4	1	0
57	8	3	2	0
58	7	3	9	2
59	7	3	14	2
60	7	3	13	2
61	7	3	12	2
62	7	3	11	2
63	6	2	12	2
64	5	2	10	2
65	5	2	9	2
66	5	2	8	1
67	5	2	8	1
68	5	2	8	1
69	4	2	8	1
70	4	2	8	1
71	4	2	8	1
72	5	2	9	2
73	6	2	12	2
74	6	2	10	2
75	6	2	15	3

1960 to 1962. This slight adjustment was again necessary to produce consistency in trend estimates.

The natural gas data were taken from Minerals Yearbooks.

Results of adding together each fuel's contribution to industrial NO_x and SO_x are listed in Table A-8.

Commercial and Residential

Emission factors for residential and commercial consumption of fuels vary considerably depending on the sulfur content of the fuel burned and the type of boiler used. The factors used here were chosen so that the results in 1973 would be consistent with the emissions for each state reported in NEDS.

Commercial and residential boilers were assumed to use coal that contained 1.3% and 0.7% sulfur respectively. Minerals Yearbooks list the sulfur contents of residual fuel oils for the years 1971-1975; these were averaged to produce the 1.4% sulfur figure that was used here. Distillate fuel oil was taken to be 0.2% sulfur since AP-42 reports it to be less than 0.3%.

Coal use data for the years 1960-1975 were taken directly from FEDS. For earlier years, Minerals Yearbooks provided retail coal sales data for the entire United States. These data were multiplied by a state/U.S. distribution factor obtained by averaging (over 1960 and 1961) the ratios of statewide commercial and residential coal use reported in FEDS to the United States total retail coal sales listed in the Minerals Yearbooks. The resulting data were adjusted according to population growth for the years 1948 to 1959.

FEDS provides fuel oil use data for the 1960-1975 years. Tables of sales of range oil and heating oils, distillate and residual, found in yearly "Mineral Industry Surveys" (BOM, 1949, 1951, 1953, 1955, 1957-1962) were used to supply data for earlier years.

The natural gas use data were taken directly from Minerals Yearbooks.

The estimated emissions resulting from the residential and commercial burning of coal, fuel oils, and natural gas were summed to produce the results presented in Table A-9.

TABLE A-8. TRENDS IN SO_X AND NO_X EMISSIONS FROM INDUSTRIAL SOURCES

	Arizona (tons/day)		Colorado (tons/day)		Nevada (tons/day)		Utah (tons/day)	
YEAR	SO_X	NO_X	SO_X	NO_X	SO_X	NO_X	SO_X	NO_X
48	9	18	50	65	6	8	64	54
49	5	20	45	61	5	6	59	50
50	2	19	49	69	6	9	75	56
51	2	23	53	72	8	10	80	64
52	2	27	50	67	9	11	75	63
53	2	28	54	73	10	11	77	69
54	2	29	44	68	5	10	67	59
55	2	30	53	79	5	10	76	60
56	2	32	54	82	4	10	79	66
57	2	34	53	77	5	11	76	65
58	2	31	48	81	4	12	63	58
59	2	29	46	80	3	11	69	63
60	3	29	50	85	4	10	66	64
61	3	37	52	81	4	12	66	63
62	3	36	53	88	4	14	74	73
63	2	35	46	92	3	13	73	76
64	2	26	55	95	3	11	85	86
65	3	47	53	104	2	13	90	90
66	4	55	51	98	2	11	96	89
67	3	39	47	83	1	8	90	83
68	3	20	54	90	1	7	92	88
69	3	21	50	86	1	8	97	93
70	3	25	52	88	3	11	85	90
71	4	31	44	94	4	15	84	91
72	7	37	54	87	6	15	87	93
73	9	45	56	98	5	14	95	102
74	9	39	59	93	5	12	101	105
75	7	31	63	91	3	10	101	101

TABLE A-9. TRENDS IN SO_X AND NO_X EMISSIONS FROM COMMERCIAL/RESIDENTIAL SOURCES

	Arizona (tons/day)		Colorado (tons/day)		Nevada (tons/day)		Utah (tons/day)	
YEAR	SO_X	NO_X	SO_X	NO_X	SO_X	NO_X	SO_X	NO_X
48	1	4	36	14	4	2	33	11
49	1	4	38	15	5	2	36	12
50	1	4	40	15	5	2	26	10
51	1	4	33	16	4	2	32	12
52	1	4	32	15	4	2	31	11
53	2	4	28	15	4	2	29	10
54	1	3	29	16	4	1	26	10
55	1	4	31	16	3	1	28	11
56	1	4	28	15	4	1	27	11
57	0	4	22	15	3	1	21	10
58	1	6	20	13	3	1	18	9
59	1	8	22	17	3	2	16	8
60	1	8	19	16	4	2	19	10
61	1	6	24	18	5	2	26	12
62	1	6	28	20	4	2	30	14
63	1	5	26	19	4	2	27	14
64	1	8	28	22	4	2	22	13
65	1	7	23	23	6	3	20	12
66	1	7	22	25	6	3	18	11
67	0	6	22	24	3	2	18	12
68	1	8	21	24	3	3	17	11
69	1	8	23	26	2	3	20	13
70	1	9	17	26	6	4	17	12
71	2	11	14	26	4	5	24	15
72	2	11	16	27	3	4	18	13
73	1	13	14	29	2	4	20	14
74	2	14	11	28	2	4	27	15
75	2	17	8	31	1	5	19	13

Evaporative Hydrocarbons

The amounts of hydrocarbons emitted by the evaporation of solvents were estimated using the 1973 emissions reported in NEDS as a base. Solvent evaporation in each state was then assumed to vary as the state's population. Population figures were interpolated from data in Statistical Abstract of the United States: 1975 (U.S. Bureas of the Census, 1975).

Estimates of emission from gasoline evaporation were also made using the NEDS data as a base. These, however, were taken to vary as the total amount of motor fuel consumed in each state varied according to Highway Statistics: Summary to 1975 (DOT, 1975).

Evaporative emissions are all non-methane according to Trijonis and Arledge (1976) so no correction was made to produce the non-methane numbers appearing in Table A-10.

TABLE A-10. TRENDS IN NMHC EMISSIONS FROM GASOLINE EVAPORATION AND SOLVENT EVAPORATION

	NMHC Evaporation (tons/day)							
	Gasoline				Solvents			
YEAR	Arizona	Colorado	Nevada	Utah	Arizona	Colorado	Nevada	Utah
48	6	10	2	5	12	17	1	8
49	6	10	2	5	12	17	1	9
50	7	11	2	5	12	18	1	9
51	8	12	3	6	13	18	1	9
52	9	13	3	6	14	19	2	9
53	9	14	3	7	15	19	2	10
54	10	14	4	7	16	20	2	10
55	10	15	4	7	17	20	2	10
56	11	16	4	8	17	21	2	10
57	12	17	4	8	19	22	2	11
58	13	17	4	9	20	22	2	11
59	14	18	5	9	21	23	2	11
60	15	19	5	9	22	24	3	11
61	16	19	5	10	21	24	3	12
62	17	20	6	10	24	25	3	12
63	18	21	7	10	25	25	3	12
64	19	21	7	11	25	26	4	12
65	19	22	7	11	26	27	4	13
66	20	23	8	12	27	27	4	13
67	21	24	8	12	28	28	4	13
68	23	26	9	13	28	28	4	13
69	26	27	9	14	29	29	4	13
70	28	30	10	15	30	30	4	14
71	30	32	11	16	31	31	4	14
72	34	35	12	17	33	32	5	14
73	37	37	12	18	34	33	5	15
74	35	35	12	18	36	33	5	15
75	36	37	13	18	37	34	5	15

REFERENCES FOR APPENDIX A

AAR (Association of American Railways), "Statistics of Railways of Class I in the United States: Calendar Years 1946 to 1956", Washington, D.C., August 1957.

AAR (Association of American Railways), "Statistics of Railways of Class I in the United States: Years 1956 to 1966", Washington, D.C., August 1967.

AAR (Association of American Railways), "Statistics of Railways of Class I in the United States: Years 1965 to 1975", Washington, D.C., January 1977.

BOM (Bureau of Mines), Minerals Yearbook, 1948-1975, U.S. Department of the Interior, Washington, D.C.

BOM (Bureau of Mines), "Mineral Industry Surveys", Annual Reports: 1949, 1951, 1953, 1955, 1957-1962, U.S. Department of the Interior, Washington, D.C.

DOE (Department of Energy), Steam-Electric Plant Air And Water Control Data, Annual Reports: 1969-1973, Washington, D.C.

DOE (Department of Energy), Federal Energy Data System (FEDS) Statistical Summary, DOE/EIA-0031/2, UC-13, February 1978.

DOT (Department of Transportation), Highway Statistics: Summary to 1965, Federal Highway Administration, Bureau of Public Roads, Washington, D.C., March 1967.

DOT (Department of Transportation), National Personal Transportation Study: Annual Miles of Automobile Travel, Report #2, Federal Highway Administration, Washington, D.C., April 1972.

DOT (Department of Transportation), Highway Travel Forecasts, Washington, D.C., November 1974.

DOT (Department of Transportation), Highway Statistics: Summary to 1975, Federal Highway Administration, Washington, D.C.

EPA (Environmental Protection Agency), NEDS (1973 National Emissions Report), Research Triangle Park, North Carolina, May 1976.

FPC (Federal Power Commission), Steam-Electric Plant Construction Cost and Annual Production Expenses, Annual Reports: 1948-1975, Washington, D.C.

Heaney, R.J., Environemntal Affairs Division of the Utah Copper Division of Kennecott Copper Corporation, Salt Lake City, Utah, 1978.

Larson, N.I. and P.E. Billings, First Annual Report on Arizona Copper Smelter Pollution Control Technology, Arizona Department of Health Services, Phoenix, Arizona, 1977.

MVMA (Motor Vehicle Manufacturers Association), 1975 Automobile Facts and Figures, Detroit, Michigan.

MVMA (Motor Vehicle Manufacturers Association), Motor Vehicle Facts and Figures '77, Detroit, Michigan.

Perry, H. and J.A. Decarls, "The Search for Low Sulfur Coal", Mechanical Engineering, Vol. 89, pp. 22-27, April 1967.

Trijonis, J. and K. Arledge, "Utility of Reactivity Criteria in Organic Emission Control Strategies: Application to the L.A. Atmosphere", EPA-600/3-76-091, August 1976.

U.S. Bureau of the Census, Statistical Abstract of the United States: 1975, 96th Edition, Washington, D.C., 1975.

U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, AP-42, 3rd Edition, Research Triangle Park, N.C., August 1977.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Kennecott, McGill, Copper Smelter", Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036c, February 1976.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Phelps Dodge, Morenci, Copper Smelter", Prepared for EPA Industrial Environemntal Research Laboratory, EPA-600/2-76-036g, Feb. 1976.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Asarco, Hayden, Copper Smelter", Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036j, February 1976.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Kennecott, Hayden, Copper Smelter", Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036b, February 1976.

Williamson, S.J., Fundamentals of Air Pollution, Addison-Wesley, Reading, Massachussetts, 1973.

APPENDIX B

PRIMARY SULFATE EMISSIONS FROM COPPER SMELTERS

Over the past three decades, copper smelters have been the dominant source of sulfur oxide emissions in the Southwest United States.* That the SO_x emissions from copper smelters significantly affect sulfate and visibility in the Southwest was demonstrated in an earlier TSC report (Trijonis and Yuan 1978), which showed that the 9 month copper strike of 1967-1968 produced substantial reductions in sulfate and increases in visibility on a large spatial scale. Lockwood and Hartman (1970), Trijonis and Yuan (1978), and Latimer et al (1978) also demonstrated that historical visibility trends in the Southwest closely followed trends in copper smelter SO_x emissions; visibility deteriorated as copper smelter SO_x emissions increased from the early 1950's to 1972, and visibility improved from 1972 to 1976 as smelter SO_x emissions were halved by air pollution controls and reduced copper production.

There is concern that the recent improving trend in visibility may be reversed in the future if SO_x emissions increase greatly as a result of new power plants and other energy developments in the Southwest. One argument against this concern is that power plant SO_x emissions may be less important (per ton) with respect to sulfates and visibility than are smelter SO_x emissions. Specifically, power plant SO_x might be less important than smelter SO_x because power plant SO_x might contain a much smaller fraction of primary sulfate emissions. In order to resolve this argument there is a need to compare primary sulfate emissions from power plants with that from smelters.

There are numerous measurements available on the percentage of sulfur emitted as sulfates (mostly SO_3) from power plants. For coal-fired power plants various data indicate the following: 0.5-1.0% (Bailey and Ruddock 1978), 2.4% (Richards et al 1975), 1-2% (Nader 1978a; Cheney and Homolya 1978),

*Here we define the Southwest as Arizona, Colorado, Nevada, New Mexico, and Utah. In the late 1960's and early 1970's, copper smelters accounted for more than 90% of total SO_x emissions in these five states.

and 0.7-1.8% (Howes 1978). For oil-fired power plants, data show 2-3% (Dietz and Wieser 1978; O'Neal et al 1978), 2.7% (Richards et al 1975), up to 10% (Nader 1978b; Homolya and Cheney 1978), and 3.4% (Howes 1978). The consensus is that primary sulfate comprises approximately 0.5-2% of sulfur emissions from coal fired power plants and 2-10% of sulfur emissions from oil fired power plants (Wilson et al 1978).

There has been much less discussion in the literature concerning primary sulfate emissions from smelters. In a search for primary sulfate emission data for smelters, we contacted approximately 25 individuals in the smelter industry, environmental research firms, universities, research laboratories, EPA, and other governmental agencies. This search uncovered the data listed in Table B-1; these data include stack tests as well as plume measurements taken a few kilometers downwind of smelters.

As indicated in Table B-1, almost all the stack test data indicate that primary sulfate emissions are approximately 0.2-1.0% for both "green-feed" and "roaster" smelters.* The plume samples, at about 2-5 km downwind of smelters, indicate about 1-2% primary sulfates from both green feed and roaster smelters.** The difference between the stack and plume measurements is likely due to one of two factors. First, both types of data could be correct, with the increased sulfate at 2-5 km representing secondary sulfate formed by $SO_2 \rightarrow SO_4^{=}$ conversion after emission. This, however, would correspond to a near-stack sulfate formation rate on the order of 5% per hour, which is somewhat higher than the 1-3% per hour reported by Lusis and Wiebe (1976) based on measurements between 5 and 100 km from the stack. Second, the stack test data might represent an artificially low estimate of primary

---

*We included notations of green-feed and roaster smelters in Table B-1 because some individuals we contacted indicated that primary sulfate emissions might be much higher for green-feed smelters than they are for roaster smelters.

**One other set of plume data (Kendall et al 1976) indicates much higher levels of primary sulfates, 11% or greater. The measurement techniques used for this data, however, are considered extremely unreliable (Kendall 1978). For example, data from these tests yield unbelievable sulfate conversion rates of 50-100% per hour.

Reproduced from best available copy.

TABLE B-1. DATA ON PERCENT PRIMARY SULFATES FROM SMELTERS

SMELTER	SMELTER TYPE	DATA SOURCE	MEASUREMENT METHODS	DISTANCE FROM STACK	NUMBER OF SAMPLES	PERCENT OF EMITTED SULFUR THAT IS SULFATE
			STACK TESTS			
Phelps Dodge/Ajo (AZ) (Copper)	Green-Feed	Steiner (1973)	EPA Method 8 (1 impinger for sulfates, 2 impingers for SO_2). Note that test is preceded by EPA Method 5 test (glass fiber filter for total particulate sample).	0	8	0.2%
Magma/San Manuel (AZ) (Copper)	Green-Feed	Bowerman (1978)	" "	0	3	0.4%
Kennecott/Hayden (AZ) (Copper)	Roaster	Bowerman (1978)	" "	0	6	0.3%
Various Arizona Smelters (Copper)	Green-Feed and Roaster	Mercer (1978)	EPA Method 8 (preceded by EPA Method 5)	0	~15	~0.5 to 1.0%
White Pine/White Pine (MI) (Copper)	Green-Feed	Weisenberg and Serne (1976a)	Not Reported	0	Not Reported	0.6%
Kennecott/McGill (NV) (Copper)	Green-Feed	Weisenberg and Serne (1976c)	Not Reported	0	Not Reported	3.0%
Kennecott/Hurley (NM) (Copper)	Green-Feed	Weisenberg and Serne (1976d)	Not Reported	0	Not Reported	0.6%
Phelps Dodge/Ajo (AZ) (Copper)	Green-Feed	Weisenberg and Serne (1976f)	Not Reported	0	Not Reported	0.5 to 1.0%
			PLUME TESTS			
Kennecott/Salt Lake City (UT) (Copper)	Green-Feed	Eatough (1978)	Sierra cascade impactor for $SO_4^=$. Beckman wet chemical for SO_2.	2-3 km	3	2.1%
INCO/Sudbury (CAN) (Nickel)	Roaster	Lusis and Wiebe (1976)	Glass fiber filter for $SO_4^=$. Impregnated filters for SO_2.	~1-5 km	14	0.7 to 1.8% (10 of the 14 samples between 1.2 and 1.5%)
INCO/Sudbury (CAN) (Nickel)	Roaster	Forrest and Newman (1977); Forrest (1978)	Quartz filter for $SO_4^=$. Impregnated filters for SO_2.	~2 km	3	1.3 to 2.0%

sulfate because of measurement problems. Specifically, some of the primary sulfate may be lost in the EPA Method 5 procedure that precedes the EPA Method 8 procedure in many of the tests.

If SO_2 to sulfate conversion were the cause of the discrepancy between the stack tests and plume tests, we would conclude that primary sulfate comprises 0.2 to 1.0% of smelter SO_x emissions (i.e. the stack samples represent true primary sulfate). If the stack samples were in error, we would conclude that primary sulfates represent about 1-2% of smelter SO_x emissions, possibly slightly less if we allow for some sulfate formation between the time of emission and the time of the plume sample. In either case, we conclude that the percentage of primary sulfate from copper smelters is <u>not</u> significantly greater than the percentage of primary sulfate from power plants -- primary sulfate from smelters is apparently about the same, or significantly less, than primary sulfate from power plants.

REFERENCES FOR APPENDIX B

Bailey, E.M. and H.A. Ruddock, "Measurements of Sulfur Trioxide at TVA Coal-Fired Power Plants Using the Condenser Method," Proceedings of the Workshop on Measurement Technology and Characterization of Primary Sulfur Oxides Emission from Combustion Sources, April 24-26, 1978, Southern Pines, NC, to be published as an EPA report.

Bowerman, L., EPA Region IX, Personal Communication, June 1978.

Cheney, J.L. and J.B. Homolya, "Characterization of Combustion Source Sulfate Emissions Using a Selective Condensation Sampling System," Proceedings of the Workshop on Measurement Technology and Characterization of Primary Sulfur Oxides Emission from Combustion Sources, April 24-26, 1978, Southern Pines, NC, to be published as an EPA report.

Dietz, R.N. and R.F. Wieser, "Operating Parameters Affecting Sulfate Emissions from an Oil-Fired Power Unit," Proceedings of the Workshop on Measurement Technology and Characterization of Primary Sulfur Oxides Emission from Combustion Sources," April 24-26, 1978, Southern Pines, NC, to be published as an EPA report.

Eatough, D., Brigham Young University, Personal Communication, June 1978.

Forrest, H. and L. Newman, "Oxidation of Sulfur Dioxide in the Sudbury Smelter Plume," Atmospheric Environment, Vol. 11, 1977.

Forrest, J., Brookhaven National Laboratories, Personal Communication, June 1978.

Homolya, J.B. and J.L. Cheyne, "An Assessment of Sulfuric Acid and Sulfate Emissions from the Combustion of Fossil Fuels," Proceedings of the Workshop on Measurement Technology and Characterization of Primary Sulfur Oxides Emission from Combustion Sources, April 24-26, 1978, Southern Pines, NC, to be published as an EPA report.

Howes, J., Battelle Memorial Laboratory, Personal Communication, June 1978.

Kendall, S.B., et al., "A Kinetics Study of the Sulfur Species in Smelter Emissions," under NSF Grant GY - 10801, University of Arizona, 1976.

Kendall, S.B., Phelps Dodge Corporation, Personal Communication, June 1978.

Latimer, D.A., et al., "The Development of Mathematical Models for the Prediction of Anthropogenic Visibility Impairment," Prepared at Systems Applications, Inc. for USEPA under Contract # 68-01-3947, 1978.

Lockwood, G.W. and W.K. Hartman, "Visibility Variations at Tucson, Arizona and Kitt Peak National Observatory," Publications of the Astronomical Society of the Pacific, Vol. 82, 1970.

Lusis, M.A. and H.A. Wiebe, "The Rate of Oxidation of Sulfur Dioxide in the Plume of a Nickel Smelter Stack," Atmospheric Environment, Vol, 10, 1976.

Mercer, C., Bureau of Air Quality, Arizona Department of Public Health, Personal Communication, June 1978.

Nader, J.S. (a), "Field Measurements and Characterization of Emissions from Coal-Fired Combustion Sources," Presented at the APCA 71st Annual Meeting, June 25-30, 1978, Houston, TX.

Nader, J.S. (b), Chief SSERB/EMDC, Environmental Protection Agency, Personal Communication, June 1978.

O'Neal, A.J., H. Cowherd, and F.W. Lipfert, "Use of a High-Flow Stack Sampler for Determination of Particulate Sulfate Emissions," Proceedings of the Workship on Measurement Technology and Characterization of Primary Sulfur Oxides Emission from Combustion Sources, April 24-25, 1978, Southern Pines, NC, to be published as an EPA report.

Richards, J., et al., "Stationary Source Control Aspects of the Ambient Sulfates and Nitrates Issues," Prepared for the USEPA/ORD under Contract # 68-02-1321, 1975.

Steiner, J., ACARAX Inc., Personal Communication, June 1978.

Trijonis, J. and K. Yuan, "Visibility in the Southwest: An Exploration of the Historical Data Base," Prepared at Technology Service Corporation for EPA Office of Planning and Evaluation and EPA Office of Research and Development under Grant # 802815, 1978.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: White Pine Copper Smelter," Prepared for EPA Industrial Research Laboratory, EPA-600/2-76-036a, February 1976.

Weisenberg, I. J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Kennecott, McGill, Copper Smelter, Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036c, February 1976.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Kennecott, Hurley, Copper Smelter," Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036d, February 1976.

Weisenberg, I.J. and J.C. Serne, "Design and Operating Parameters for Emission Control Studies: Phelps Dodge, Ajo Copper Smelter," Prepared for EPA Industrial Environmental Research Laboratory, EPA-600/2-76-036f, February 1976.

Wilson, W.E., et al., "Dependence of Ambient Sulfates on Precursor Control: Chemical Aspects," Presented at the AIChE Meeting, June 4-8, 1978, Philadelphia, PA.

APPENDIX C

ESTIMATING AQCR EMISSION TRENDS FROM STATE EMISSION TRENDS

Chapter 2 of this report presents historical emission trends from 1948 to 1975 in four Southwestern states. For some of the analyses performed in Chapter 5, it is also necessary to know emission trends for individual Air Quality Control Regions (AQCR's). This appendix explains how AQCR emission trends for Phoenix/Tucson, Denver, and Salt Lake City can be estimated from state emission trends for Arizona, Colorado, and Utah respectively.

There are essentially three factors which determine total emission trends for a given pollutant in a certain region: (1) the relative contributions (for some base year) of each source category to total emissions, (2) changes in emission factors (from air pollution controls, fuel switches, etc.) for individual source categories, and (3) growth or attrition rates for individual source categories. It appears to be a fairly good approximation to make the fairly crude assumption that, for each of the three AQCR's, these three factors have operated in a way that kept AQCR emissions at a nearly constant percentage of state emissions. With respect to the first factor, Tables C-1 to C-3 compare the distribution of emissions by source type in 1973. It is evident that for each pollutant, the distribution of emissions by source type is nearly the same in each AQCR as it is in the corresponding state. With respect to the second factor, we can expect that changes in emission factors would tend to be rather uniform within each state. This is certainly true of the changes produced by automotive controls, and it should be approximately true with respect to fuel changes (e.g. the switch from coal to diesel oil in railroading, the switch to cleaner fuels for residential and commercial sources, etc.). With respect to the third factor, we have no data comparing individual source growth rates in each AQCR with corresponding statewide source growth rates. However, population growth should be a fairly good indicator of overall source growth rates in AQCR's versus states. Comparative population statistics for metropolitan areas and states are readily available only for 1960-1973 (USBOC, 1975); these data indicate that the three metropolitan areas have grown

TABLE C-1. COMPARISON OF SOURCE DISTRIBUTIONS FOR PHOENIX/TUCSON AQCR EMISSIONS AND TOTAL ARIZONA EMISSIONS (EPA, 1976)

	SO_x		NO_x		NMHC	
	Phoenix/ Tucson	Arizona	Phoenix/ Tucson	Arizona	Phoenix/ Tucson	Arizona
Total Emissions (tons/day)	1960	5620	329	463	479	630
DISTRIBUTION BY SOURCE CATEGORY (PER CENT OF TOTAL)						
Cu Smelters	98	99	---	---	---	---
Gasoline Vehicles	0.3	0.1	51	49	68	66
Diesel Vehicles	---	---	12	15	---	---
Railroads	0.2	0.1	7	6	---	---
Power Plants	0.3	0.3	19	17	---	---
Industrial	0.1	0.1	2	3	---	---
Commercial & Residential	0.1	0.1	3	3	---	---
Gasoline Evaporation	---	---	---	---	5	6
Solvent Evaporation	---	---	---	---	6	5
Other	1.1	0.3	6	7	20	23

TABLE C-2. COMPARISON OF SOURCE DISTRIBUTIONS FOR DENVER AQCR EMISSIONS AND TOTAL COLORADO EMISSIONS (EPA, 1976)

	SO_x		NO_x		NMHC	
	Denver	Colorado	Denver	Colorado	Denver	Colorado
Total Emissions (tons/day)	69	131	271	508	314	602
DISTRIBUTION BY SOURCE CATEGORY (PER CENT OF TOTAL)						
Gasoline Vehicles	---	---	46	49	75	76
Diesel Vehicles	---	---	11	11	---	---
Railroads	4	4	7	6	---	---
Power Plants	46	45	18	17	---	---
Industrial	24	20	9	9	---	---
Commercial & Residential	6	11	6	6	---	---
Petroleum Industry	8	4	1	0.4	---	---
Gasoline Evaporation	---	---	---	---	6	6
Solvent Evaporation	---	---	---	---	7	5
Other	12	16	2	2	11	12

TABLE C-3. COMPARISON OF SOURCE DISTRIBUTIONS FOR SALT LAKE CITY AQCR EMISSIONS AND TOTAL UTAH EMISSIONS (EPA, 1976)

	SO_x		NO_x		NMHC	
	Salt Lake City	Utah	Salt Lake City	Utah	Salt Lake City	Utah
Total Emissions (tons/day)	461	501	194	295	166	270
DISTRIBUTION BY SOURCE CATEGORY (PER CENT OF TOTAL)						
Cu Smelters	49	45	---	---	---	---
Gasoline Vehicles	---	---	34	38	61	63
Diesel Vehicles	---	---	9	12	---	---
Railroads	1	1	8	11	---	---
Power Plants	5	7	9	10	---	---
Industrial	15	15	22	16	---	---
Commercial & Residential	3	4	7	5	---	---
Petroleum Industry	10	9	7	4	---	---
Gasoline Evaporation	---	---	---	---	6	6
Solvent Evaporation	---	---	---	---	7	5
Other	18	19	4	4	25	26

slightly more rapidly than their respective states -- Phoenix/Tucson (4.0% per year) versus Arizona (3.4% per year), Denver (3.0% per year) versus Colorado (2.6% per year), and Salt Lake City (2.1% per year) versus Utah (1.9% per year). Rudimentary sensitivity analyses indicate that these relative differences in growth rates produce effects that are small compared to the overall effect of source growth on emissions.

Based on the above discussion, we have decided to assume that emission trends in each of the three AQCR's are approximately a constant factor times emission trends in the corresponding state. The factors for calculating AQCR emissions are listed in Table C-4. Because of the crude nature of the assumed constant relationship between AQCR emissions and state emissions, we are not as confident of the AQCR emission trends as we are of the state emission trends. However, the constant factors in Table C-4 should be useful in allowing the extinction/emission coefficients to represent air basin emissions (rather than state emissions) in our analyses which center on visibility trends within metropolitan areas.

TABLE C-4. FACTORS FOR DETERMINING AQCR EMISSION TRENDS FROM STATE EMISSION TRENDS

AQCR/STATE	FACTOR FOR COMPUTING AQCR EMISSIONS		
	SO_x	NO_x	NMHC
Phoenix-Tucson/Arizona	0.35	0.71	0.76
Denver/Colorado	0.53	0.53	0.52
Salt Lake City/Utah	0.92	0.66	0.61

REFERENCES FOR APPENDIX C

EPA (U.S. Environmental Protection Agency), 1973 National Emissions Report, National Emissions Data System (NEDS) of the Aerometric and Emissions Reporting System (AEROS), EPA-450/2-76-007, May 1976.

USBOC (U.S. Bureau of the Census), Statistical Abstract of the United States 1975, U.S. Department of Commerce, Washington, D.C., 1975.

APPENDIX D

STATISTICAL TESTS FOR DETERMINING THE SIGNIFICANCE OF RELOCATIONS IN VISIBILITY OBSERVATION SITES

This appendix describes the two statsitical tests for examining the effect of observation site relocations on reported visibilities. Both tests are based on quarterly median visibilities, and both use approximately four years of data (two before and two after the time of the relocation). The analysis is restricted to only two years on either side of the relocation in order to help minimize the possibility that long-term trends will be confused with the jump in visibility caused by the relocation. Quarterly values are used because they are readily computed by our data processing programs and because yearly values would yield too few data points.

Test 1. Net Jump in Quarterly Medians

The first test is best illustrated by example. Assume a relocation occurred during the 3rd quarter of 1965. Then the data points used are as follows:

1963	4th quarter median	x_1
	1st quarter median	x_2
1964	2nd quarter median	x_3
	3rd quarter median	x_4
	4th quarter median	x_5
	1st quarter median	x_6
1965	2nd quarter median	x_7
	3rd quarter median	relocation
	4th quarter median	y_1
	1st quarter median	y_2
1966	2nd quarter median	y_3
	3rd quarter median	y_4
	4th quarter median	y_5
	1st quarter median	y_6
1967	2nd quarter median	y_7

Seven quarterly changes in visibility are computed as $z_i = y_i - x_i$, $i = 1, \ldots, 7$. The estimated net jump in visibility is simply the average value ($\overline{z_i}$), and the t-statistic for the jump is $\overline{z_i}/(\sigma_z/\sqrt{7})$, where σ_z is the standard deviation of the z_i.

Test 2. Multivariate Regression Test on Seasonally Adjusted Quarterly Medians

The first test has the advantage that it is simple and automatically discounts for seasonal trends in the data. The major disadvantage is that it could easily confuse a gradual trend in the data with a jump produced by the relocation. To account for this latter possibility, we also conducted a simple multiple regression test.

The data for the regression test consist of two years of seasonally adjusted* quarterly medians before the relocation (z_{-8}, z_{-7}, ..., z_{-1}) and two years of seasonally adjusted quarterly medians after the relocation (z_1, z_2, ..., z_8). A multiple regression is then run with these 16 data points as follows:

$$z_i = a + bi + c\,H(i),$$

where H(i) is the Heavyside step function (zero for $i \leq 0$, one for $i > 0$). The coefficient "c" now represents our estimate of the net jump produced by the relocation (discounting for the net linear trend which is represented by "b"). The t-statistic is "c" divided by its standard deviation.

The regression test is explicitly designed to discount for the gradual trend in the data. However, it suffers from the possibility that distortions could be produced by the intercorrelation (R = 0.89) between the "independent" variables, "i" and "H(i)".

---

*The seasonal adjustment factors are computed as follows:

$$f_{\text{nth quarter}} = \frac{\overline{z} \text{ for all 16 values}}{\overline{z} \text{ for the 4 nth quarter values}}$$

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-450/5-79-009		PB 80 156136

4. TITLE AND SUBTITLE	5. REPORT DATE
Empirical Studies of the Relationship Between Emissions and Visibility in the Southwest	September 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Marilyn Marians and John Trijonis	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Technology Service Corporation Route 7, Box 124-K Santa Fe, New Mexico 87501	10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. Grant 802015
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Research Triangle Park, N.C. 27711	13. TYPE OF REPORT AND PERIOD COVERED Interim May 1978-March 1979 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Historical emission trends of SO_x, NO_x, and NMHC are determined year-by-year from 1948 to 1975 for four Southwestern states (Arizona, Colorado, Nevada, and Utah). Trends in visibility levels (medians and other percentiles) are documented for the period 1948-1976 at 12 airports in the Southwest.
Two analyses are used to relate emission changes to variations in regional extinction levels. The first analysis examines the air quality changes associated with a 90% reduction of Southwestern SO_x emissions during a nine-month copper strike and estimates the extinction produced by SO_x emissions on various spatial scales. The second analysis involves regression studies relating historical extinction levels from 1948-1975. Because of limitations in the analytical methods, there is a high degree of uncertainty in many of the results. However, the studies do provide insights into the effects of aerosol precursor emissions on extinction at various distances from sources. In the case of mesoscale effects of SO_x in the Southwest, quantitative coefficients are proposed which link emissions to regional extinction.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution Aerosols Sulfates Visibility Sulfur oxides emissions	Southwest	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS (This page)	22. PRICE

EPA Form 2220-1 (9-73)